The Muon Collider--
Status and Physics prospects

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International Workshop on Linear Colliders
Sitges, Barcelona
April 29,1999

Summary of talk

- Motivation
- Brief history and overview
- Proton Source
- Pion Production and decay channel
- Ionization Cooling and Mucool R&D program
- Acceleration and collider
- Backgrounds and detector
- Physics possibilities with a muon collider
  - » Higgs factory
    - Energy calibration to a part in 10^{-6} using g-2 precession
  - » Top and other threshold scans
  - » Susy and Technicolor
- Neutrino Sources
  - » Best method to produce neutrino beams of well-defined composition and flux

The Muon Collider Collaboration

Argonne National Laboratory
Brookhaven National Laboratory
CERN, Geneva, Switzerland
DESY, Hamburg, Germany
Fermi National Accelerator Laboratory
Jefferson Lab., VA
Insit. of Mathematics, Novosibirsk, Russia
High Magnetic Fields Lab., Florida State Univ
Lawrence Berkeley National Laboratory
Los Alamos National Lab.
Nat. Inst. Radiological Sciences, Ohiba, Japan
Nucl. Science Research Facility, Kyoto Univ., Japan
Princeton University
Center for Advanced Accelerators, UCLA
Cornell University
Fairfield University
Indiana University
Illinois Institute of Technology
Rockefeller University
Tel−Aviv University, Israel
University of California, Berkeley
University of California, Davis
University of Iowa
University of Mississippi
University of Virginia
University of Wisconsin
BINP, Novosibirsk, Russia
KEK, Tsukuba−shi, Japan

Brief History of the Muon Collider

- An old idea.. Muon colliders mentioned by Tinlot(1960), Budker(1969), Skrinsky(1971), Neuffer(1979)
- A key concept for a high luminosity muon collider is ionization cooling: Skrinsky and Parkhomchuk(1981).
- The realization that a high luminosity muon collider might be feasible (Neuffer&Palmer) resulted in a series of workshops. After the Sausalito workshop in 1995, Fermilab and BNL joined in an effort to study the concept and publish a report. The muon collider collaboration grew -->26 institutions and ~ 100 Physicists.
- -->$\mu^+\mu^-$ collider: A feasibility study, Snowmass (1996): Fermilab-conf-96/092-->feasibility of a 2x2 TeV Collider.

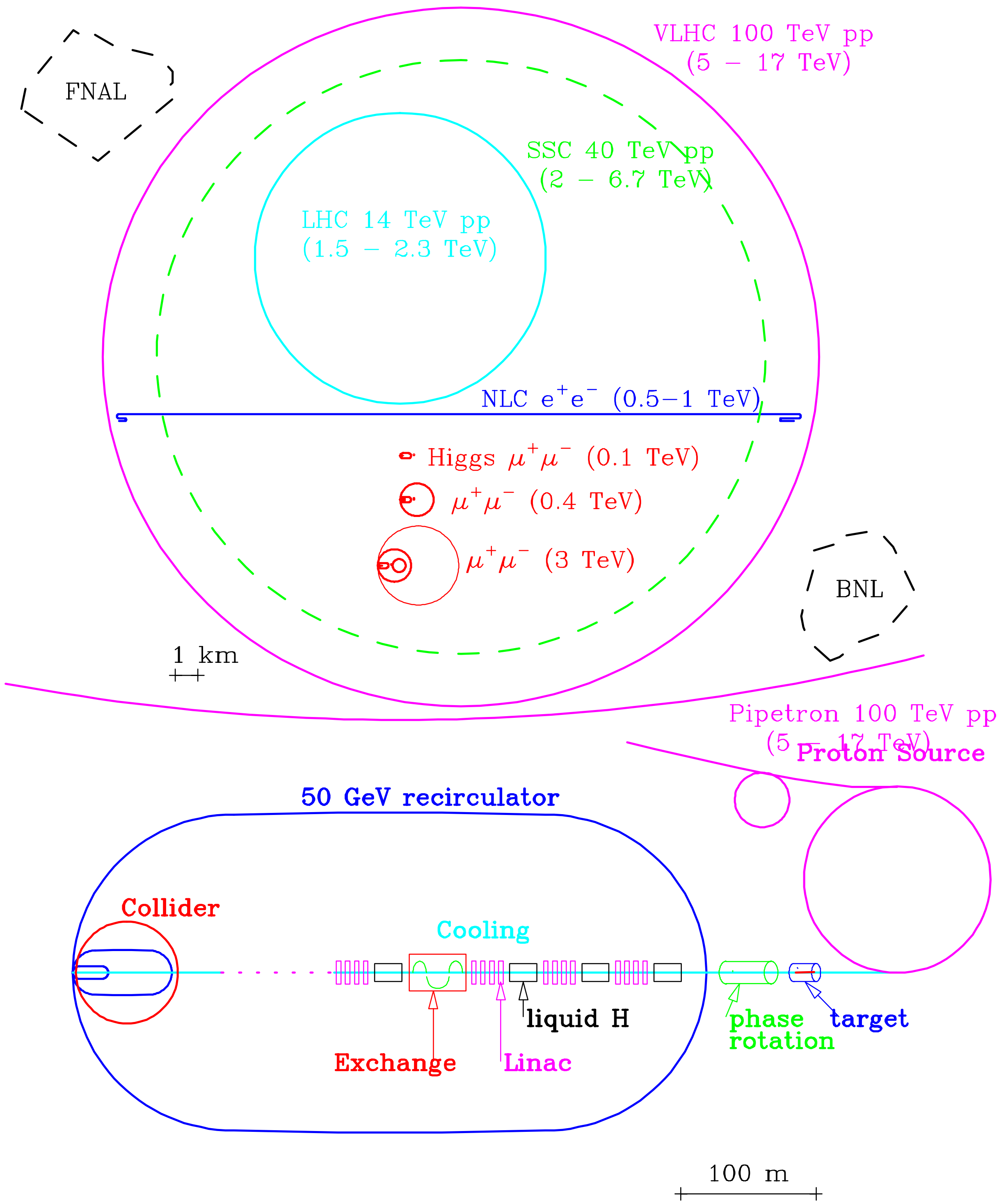
Brief History of the Muon Collider

- Although many questions were left open in the Snowmass report, no show stoppers were identified… and the muon collider collaboration has continued to develop the concepts.
- Workshop on Physics at the first Muon Collider and the front end of the muon collider- Nov 97- AIP proceedings S.Geer, R.Raja eds.
- Status of Muon Collider Research and future plans BNL-625-623,Fermilab -Pub 98/179, LBNL-41935, submitted to PRSTAB

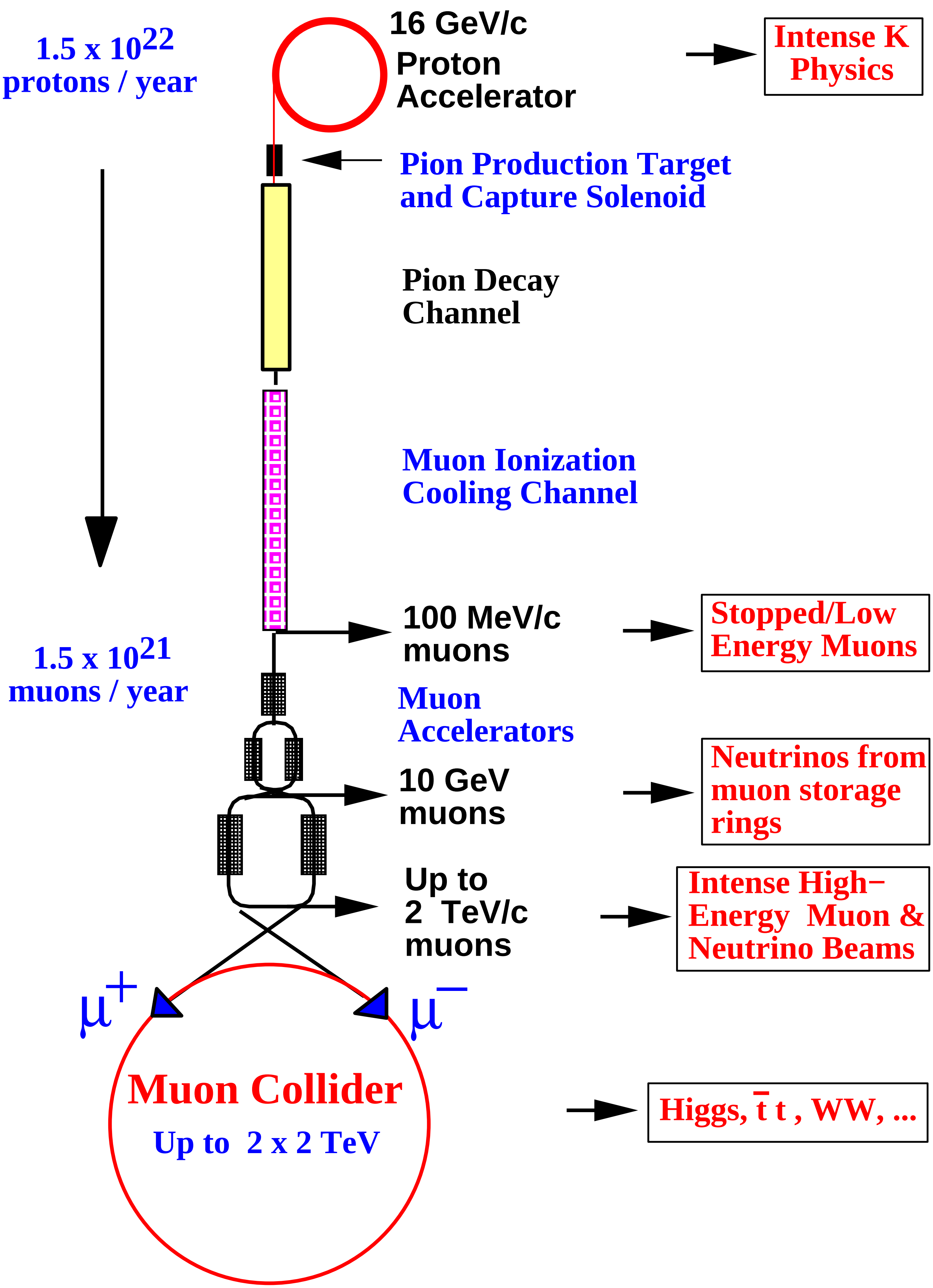
Motivation

- The muon is more massive than the electron by factor 200--> radius of acceleration not limited by synchrotron radiation. Compact machines
- $\mu^+\mu^-$ couples directly to Higgs can produce Higgs in the s channel as well as other Higgs like entities such as techni-η's,ρ's and π^0's.
- Muon can be polarized. Polarizations of 20% are easy. The above s-channel resonances can be scanned by a muon collider (A standard model Higgs at 110 GeV/c^2 mass has a width of a few MeV), since the bunch to bunch energy can be calibrated using g-2 spin precession.
- Higher energies such as 4 TeV (or higher) in the CMS are feasible, if the concept works at all.
- As one upgrades the proton driver in intensity, existing physics (e.g Tevatron experiments) benefits. Rare K decays.
- Cool muons can be used for neutrino sources, stopped muon physics. The neutrino option might be sufficient to justify this approach by itself.

Schematic of Muon Collider



Muon Collider Schematic



CANDIDATE MUON COLLIDER (E_{cm} = 500 GeV)

July 1998

FERMILAB

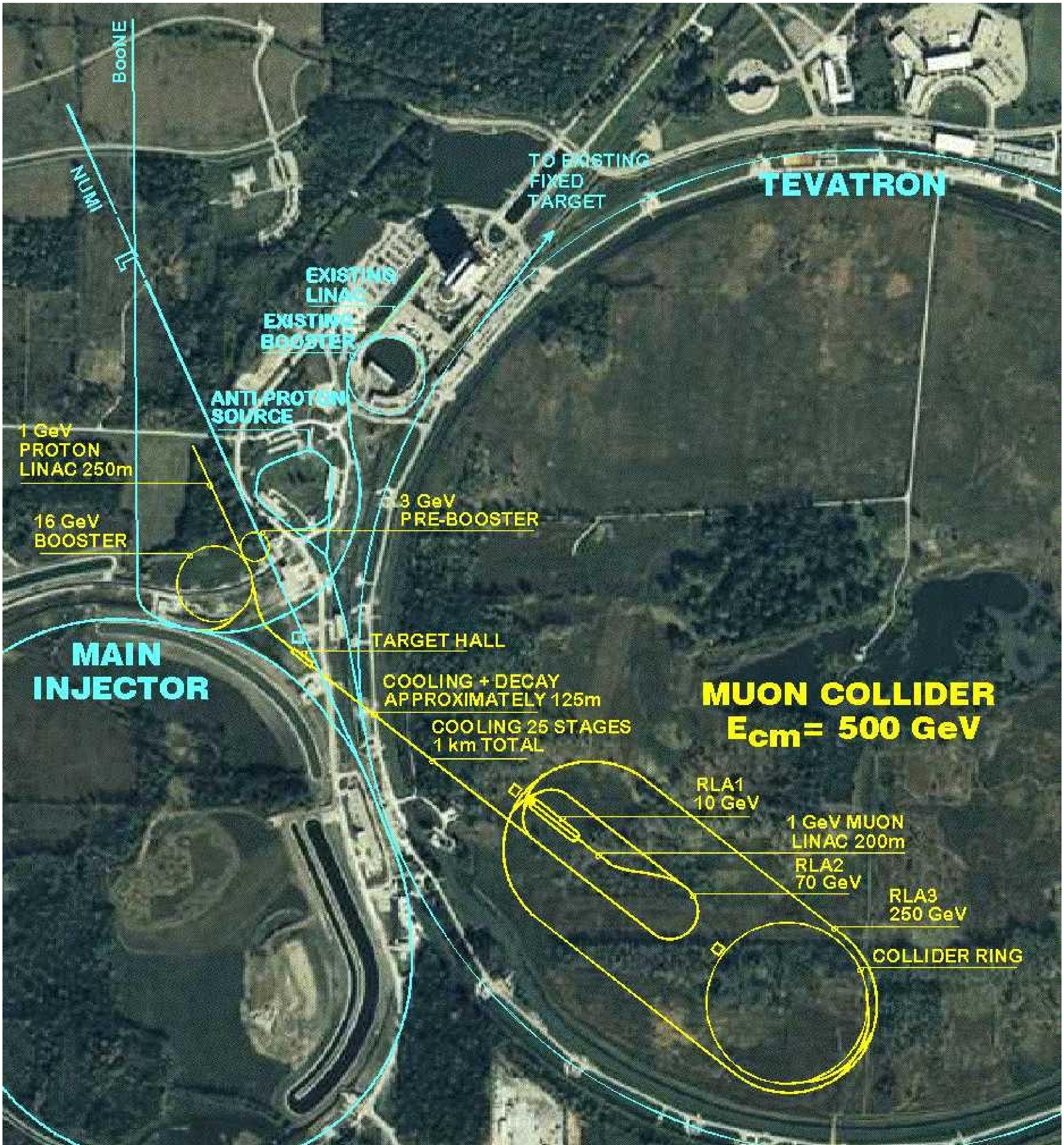


PHOTO DATE: OCTOBER 1997

Muon Collider Parameters

- **3 collider energies have been considered in some detail so far:**

	Energy (GeV)			
	50x50		200x200	1500x1500
	Broadband	Narrowband		
Rate (Hz)	15	15	15	15
Muons/bunch	4×10^{12}	4×10^{12}	2×10^{12}	2×10^{12}
Bunches	1 x 1	1 x 1	2 x 2	2 x 2
Circumference	300m	300m	1 km	6 km
Bunch σ_z (cm)	9	13	2.3	0.3
Spot σ_r (μm)	187	270	24	3.2
β^* (cm)	9	13	2.3	0.3
$\Delta E/E$ (%)	0.007	0.002	0.08	0.08
L ($cm^{-2}\,s^{-1}$)	2×10^{31}	1×10^{31}	10^{33}	5×10^{34}

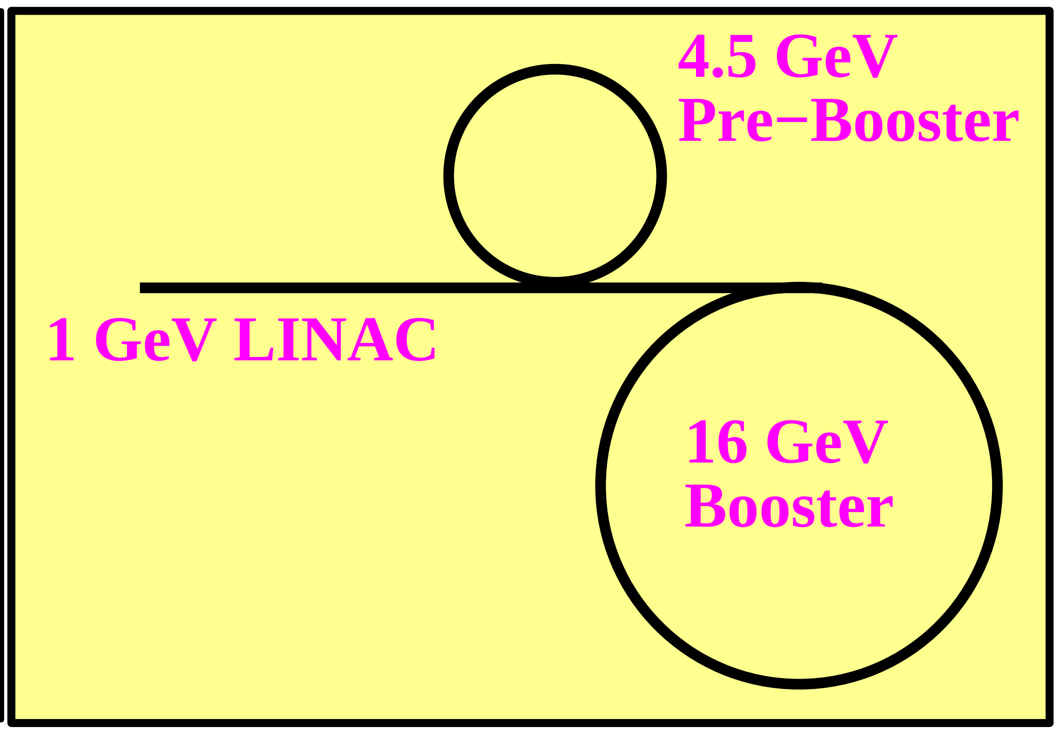
The Proton Source

- **The muon production rate is not very sensitive to the choice of proton driver energy since increased pion production at higher energy is compensated by the higher repetition rate possible at lower energy.**
- **Challenge: Need very short O(1 ns) very intense proton bunches O(10^{13}) x 15 Hz.**
- **A Development Plan for the Fermilab Proton Source**
  (S.D. Holmes et al; Fermilab−TM−2021, 1997)

Upgrade 400 MeV Linac −> 1 GeV

Upgrade 8 GeV Booster −> 16 GeV

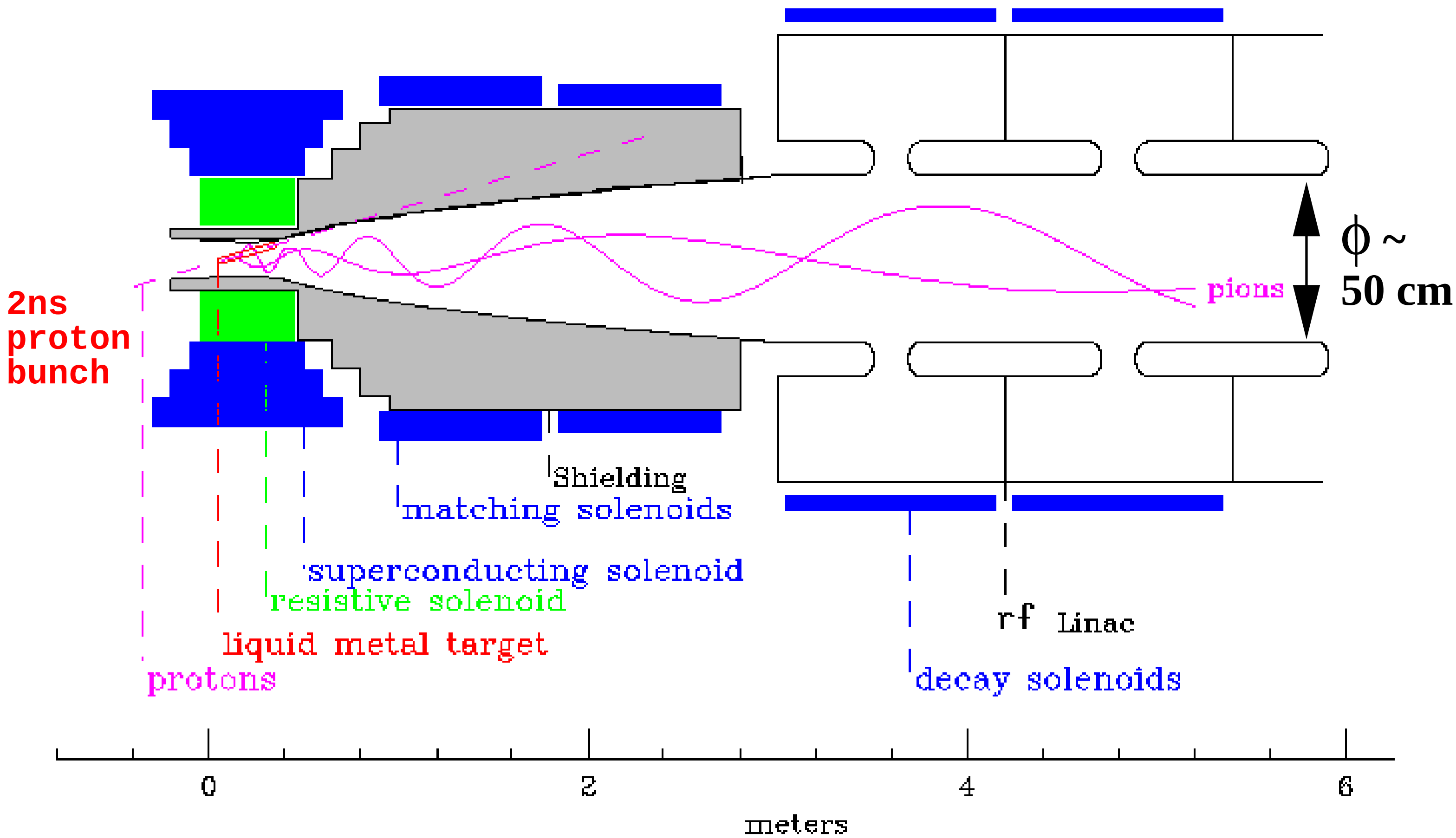
Add a 4.5 GeV (3 GeV ?) Pre−Booster (facilitates short bunches).



−> 1.5 x 10^{15} protons/sec at 16 GeV/c
(Two 2ns bunches per pulse−train x 15 Hz)

- **Design study in progress −> CDR in 2 years.**

The Pion Source and Decay Channel



16 GeV Protons

5 x 10^{13} p/bunch

x 2 bunches/pulse x 15 Hz

~ 2 x 10^{22} protons/year

→

0.6 π^+ per proton

p_z ~ 200 MeV/c

p_T ~ 200 MeV/c

$\sigma(\Delta E/E)$ ~ 1

Pion Production Target R&D

STEPS :

- **O(10^{15}) protons/sec onto a high−Z target −> 4 MW beam power !**
- **Capture pions with P_T < 200 MeV in a 20 T solenoid.**
- **Transfer pions to a 1.25 T solenoidal decay channel.**
- **Compress π/μ bunch energy spread with rf cavities.**

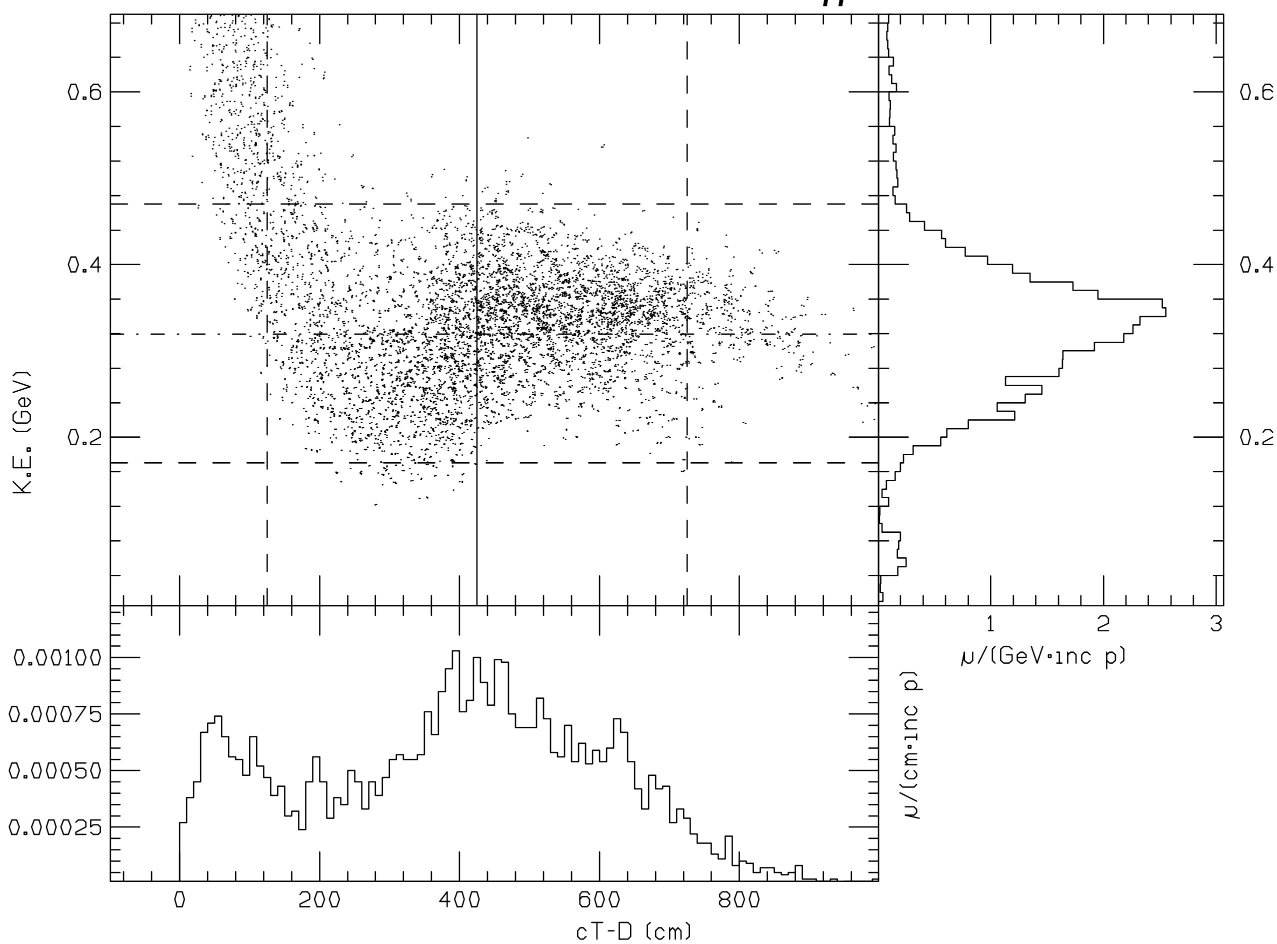
ISSUES :

- **400 KW deposited in target:**
  −> move target material away from beam & cool remotely −> baseline solution = liquid metal jet.
- **First rf cavity should be ~3 m from target:**
  −> will it operate in the radiation environment.
- **Will need high−power low frequency rf.**

Cooling Motivation

- **The pion capture decay channel produces a diffuse "cloud" of low energy (~300 MeV) muons.**

D. Neuffer **&** *A.. Van Ginneken*



- **If a high−luminosity muon collider is to become a reality, we must reduce the 6−D phase−space occupied by the"cloud" of muons coming from a pion decay channel by a factor of $10^5 - 10^6$.**

- **The cooling time must not be long compared to the muon lifetime (2μs) −> new cooling method −> Ionization Cooling (Skrinsky & Parkhomchuk, 1981).**

Ionization Cooling theory for pedestrians

- In a Hamiltonian system, a particle's motion along the beam direction may be specified by a set of 6 canonical variables $(x,p_x),(y,p_y),(z,p_z)$ or $(x,p_x),(y,p_y),(E,t)$. Let us define a 6-vector X_i ,(i=1,6), which refers to the above set. Over an ensemble of particles, let us define a 6-vector Y such that $Y_i=X_i-\langle X\rangle_i$
- Then the error matrix

$$E_{ij} = \langle Y_i Y_j \rangle$$

- Then the 6-Dimensional emittance ε_6 is defined as

$$(\varepsilon_6)^2 = \text{determinant}(E)/(m_\mu c)^6$$

- In a Hamiltonian system, the 6-vector X' at a later time is given by a linear transformation U such that

$$X' = U\,X, \quad \text{leading to } E' = UEU^T$$

- I.e. Det(E') = Det(E), emittance is preserved if Det(U)=1. Such transformations are known as Symplectic transformations. Liouville's theorem.
- Cooling is a non-Hamiltonian transformation with Det(U)<1, leading to emitance reduction.

Ionization cooling theory for pedestrians

- In the special case where correlations between x,y and z sets of variables can be neglected, the 6-dimensional emittance can be written as

$$(\varepsilon_6) = (\varepsilon^x{}_n)(\varepsilon^y{}_n)(\varepsilon^z{}_n)$$

where $\varepsilon^x{}_n$ is the normalized emittance in the x direction etc. The x and y emittances are referred to as the transverse emittance and the z emittance is known as the normalized emitance.

When angles wrt beam direction are small, it can be trivially shown that

$$(\varepsilon^x{}_n)^2 = \{<x^2><\theta^2> - <x\theta>^2\}\gamma^2\beta^2$$

- The term in the {} is known as the (unnormalized) emittance.
- Defining E as the particle energy, $\beta_\perp$ as the beta function, $\beta\gamma$ as the usual Lorentz factors and L_R as the radiation length of cooling material, and m_μ as the mass of the muon, leads to the following expressions.

Ionization cooling theory for pedestrians

- We can show
  - » rate of cooling decreases as emittance decreases
  - » Effects due to multiple scattering are ameliorated by placing absorbers at points where angular divergence of beams is large so that the additional angular spread due to MS is not a large increse in emittance. This translates to areas of small beta function.

Differentiating,

$$\frac{d\varepsilon_N^x}{dz} = \varepsilon^x \frac{d(\beta\gamma)}{dz} + \beta\gamma \frac{d\varepsilon^x}{dz}$$

----cooling--heating--

$$\frac{d\varepsilon_N^x}{dz}(cool) = -\frac{1}{\beta^2}\frac{\varepsilon_N^x}{E}\left|\frac{dE}{dz}\right|$$

$$\frac{d\varepsilon_N^x}{dz}(heat) = \frac{\beta\gamma}{2\varepsilon_x}\left\{ <x^2>\frac{d<\theta^2>}{dz} + <\theta^2>\frac{d<x^2>}{dz} - 2<x\theta>\frac{d<x\theta>}{dz} \right\}$$

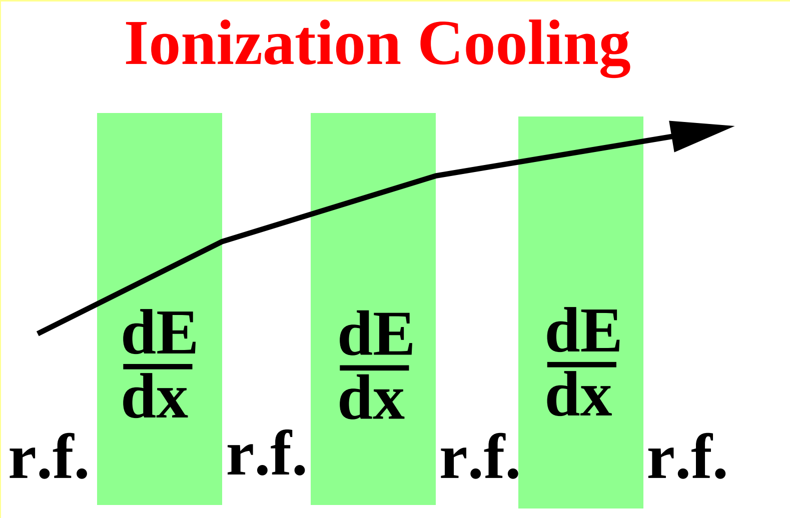
--neglecting--correlations--

$$\frac{d\varepsilon_N^x}{dz}(heat) = \beta\gamma\frac{\beta_\perp}{2}\frac{d<\theta^2>}{dz} \text{ --multiple--scattering}$$

leading--to

$$\frac{d\varepsilon_N^x}{dz} = -\frac{1}{\beta^2}\frac{\varepsilon_N^x}{E}\left|\frac{dE}{dz}\right| + \beta_\perp \frac{(0.014)^2}{2\beta^3 E m_\mu L_R}$$

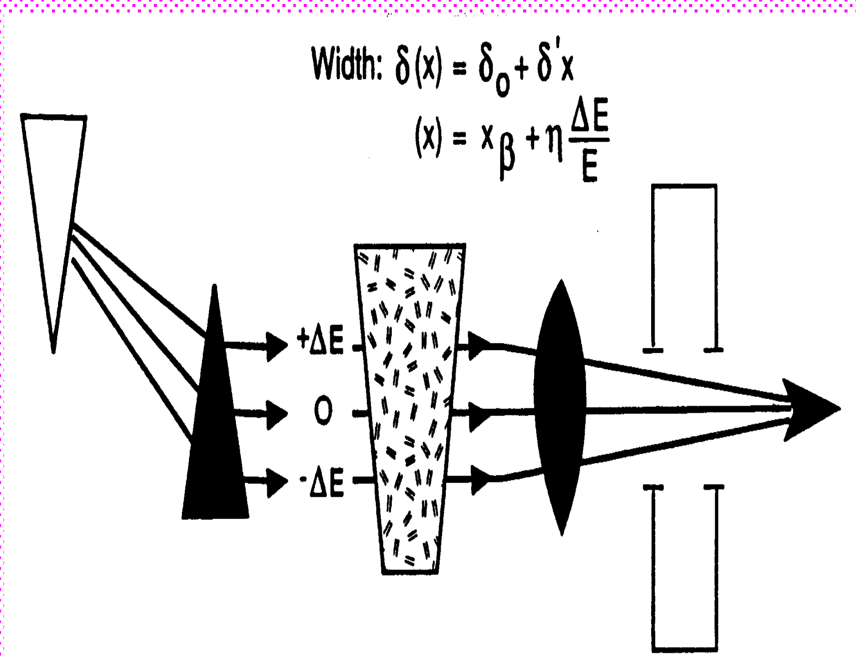
Ionization Cooling



Transverse Cooling

Muons lose energy by dE/dx and long–itudinal momentum replaced by r.f.

- **To Minimize heating from Coulomb Scattering:**
  - Small $\beta_\perp$ (strong focusing) : High–field solenoids or Lithium Lenses
  - Large L_R (low–Z absorber) : Liquid H_2



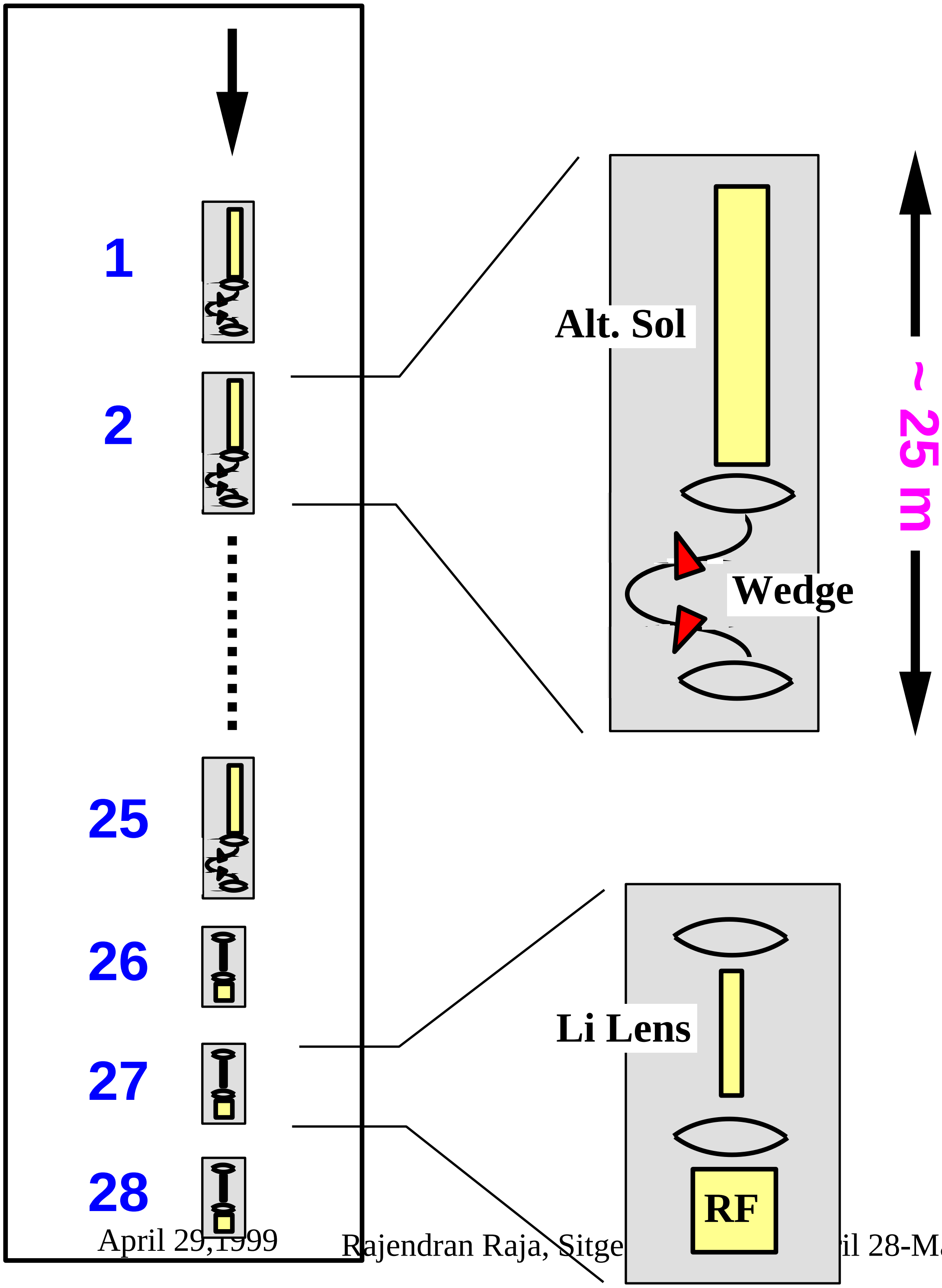
Energy "Cooling"

Ionization cooling using a wedge plus dispersion.

Exchanges emitt–ance between transverse & long–itudinal directions

Cooling Channel Concept

- A complete cooling channel for a high luminosity muon collider would consist of ~20−30 stages, each ~25m long, & each reducing the 6−D phase space by a factor of ~2.

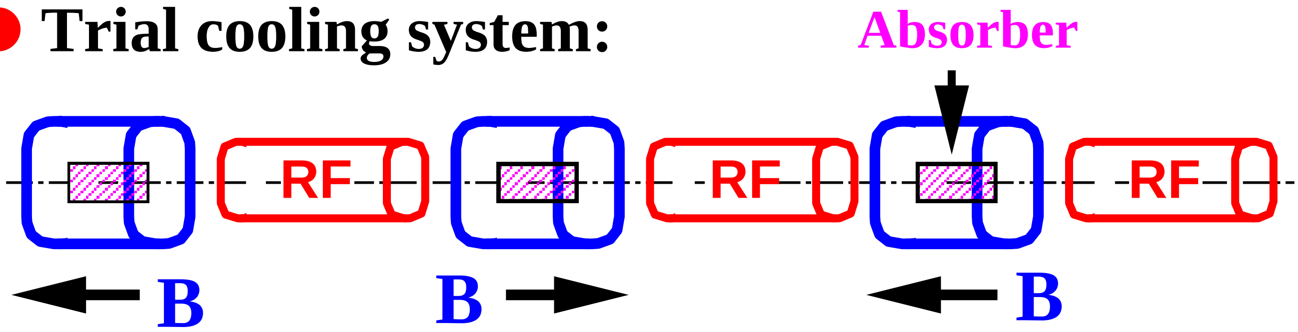


One Alternating Solenoid Stage + Emittance Exchange Section

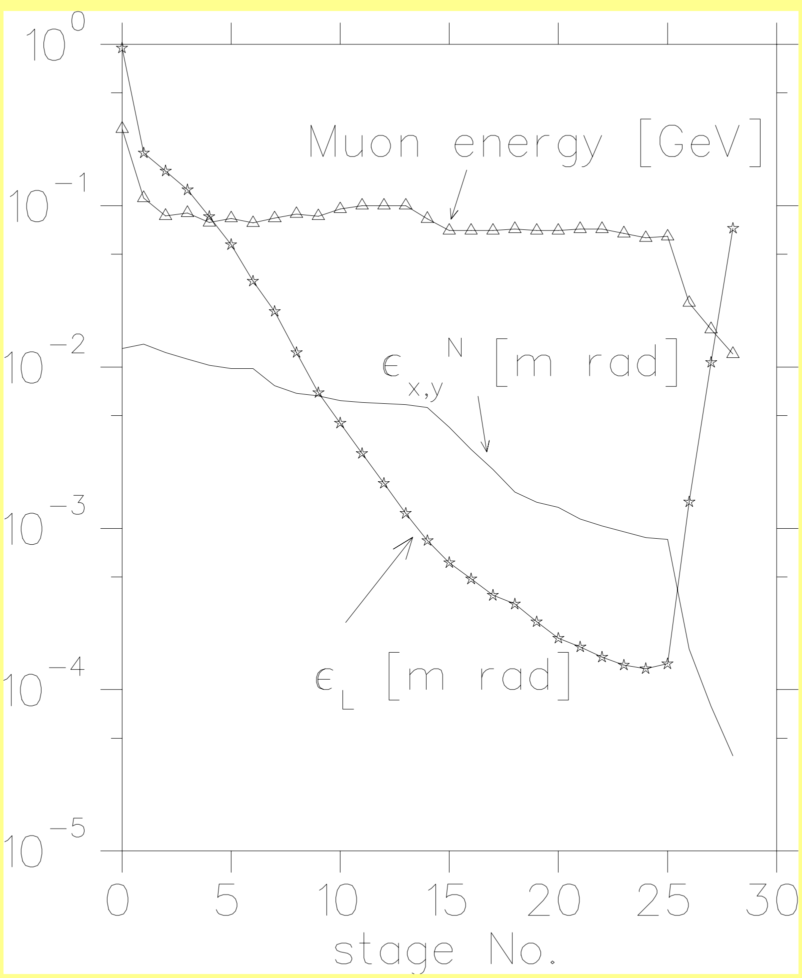
One Lithium Lens Stage

The Alternating Solenoid Channel

- **Trial cooling system:**



- **As the muons loose energy within the solenoids they loose angular momentum −> gain canonical angular momentum. To mitigate this, the the direction of the field in adjacent high−field solenoids is reversed .**



Toy Calculation

(*R. Palmer*)

Uses analytical express−ions for the β−functions, cooling+heating rates, & emittance acceptances.

Length = 750 m

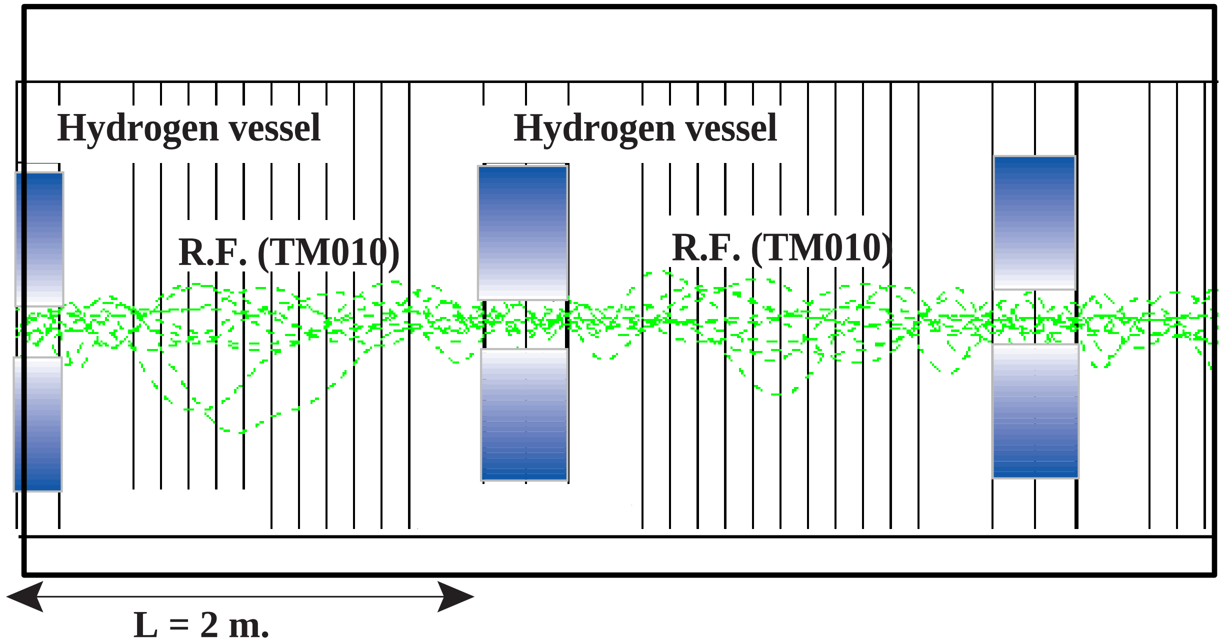
Total Reacceleration = 4.7 GeV

LiH Absorbers

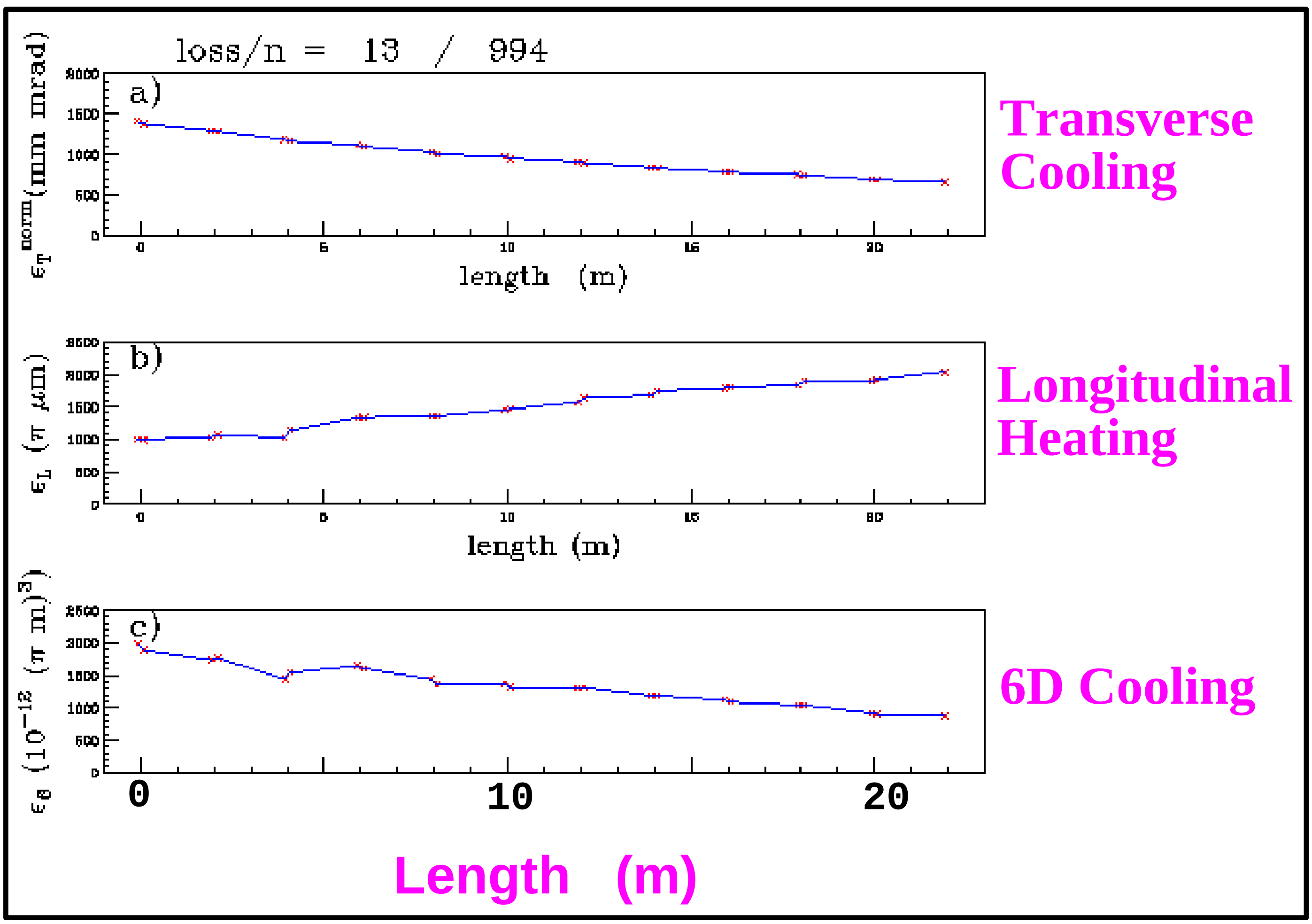
Fraction of muons that survive = 55%.

Alternating Solenoid Cooling: Simulation Results

1. DPGEANT Simulation (*P. Lebrun*)



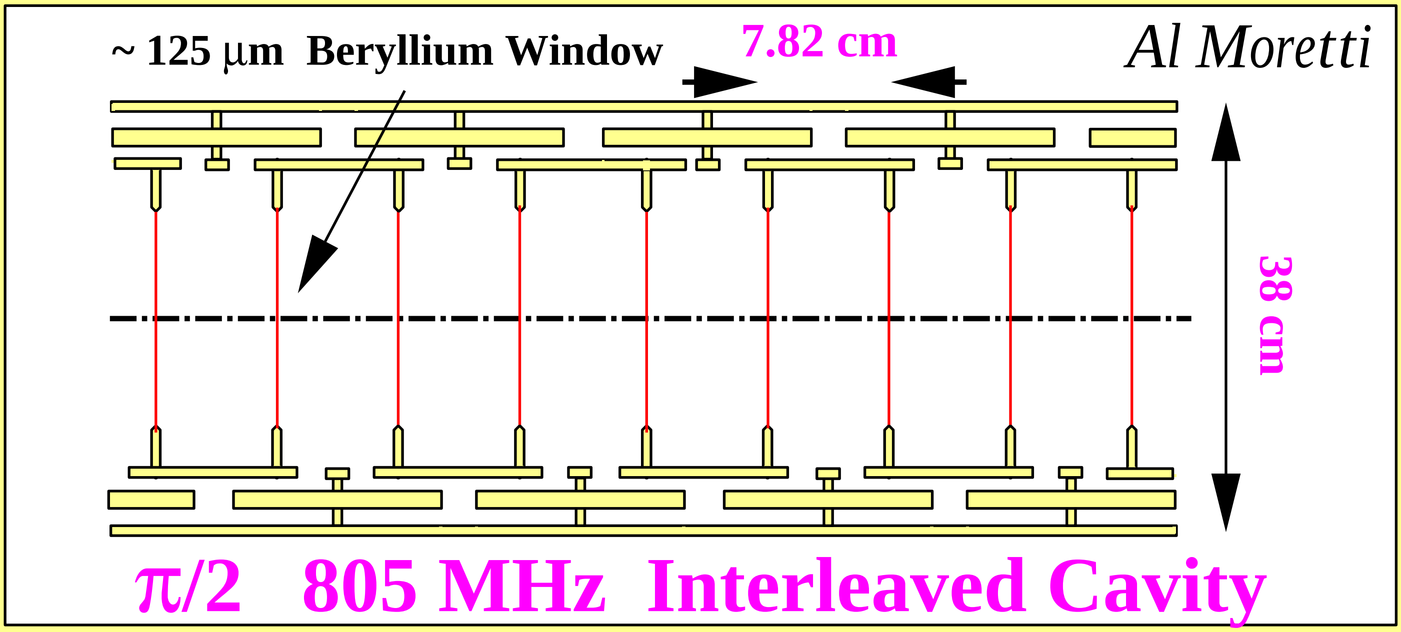
2. ICOOL Simulation (*R. Fernow*)



RF Cavity R&D

- The simulations teach us that, to keep the bunch captured ($\sigma_p/p \sim 4-6\%$) as it goes down the channel, require a high peak accelerating field −> 2 concepts

1. Since muons dont interact strongly, close the aperture in the cavity with a thin conductor ... for given peak surface field ~ doubles gradient on axis −> $E_{peak} = E_{acc}$



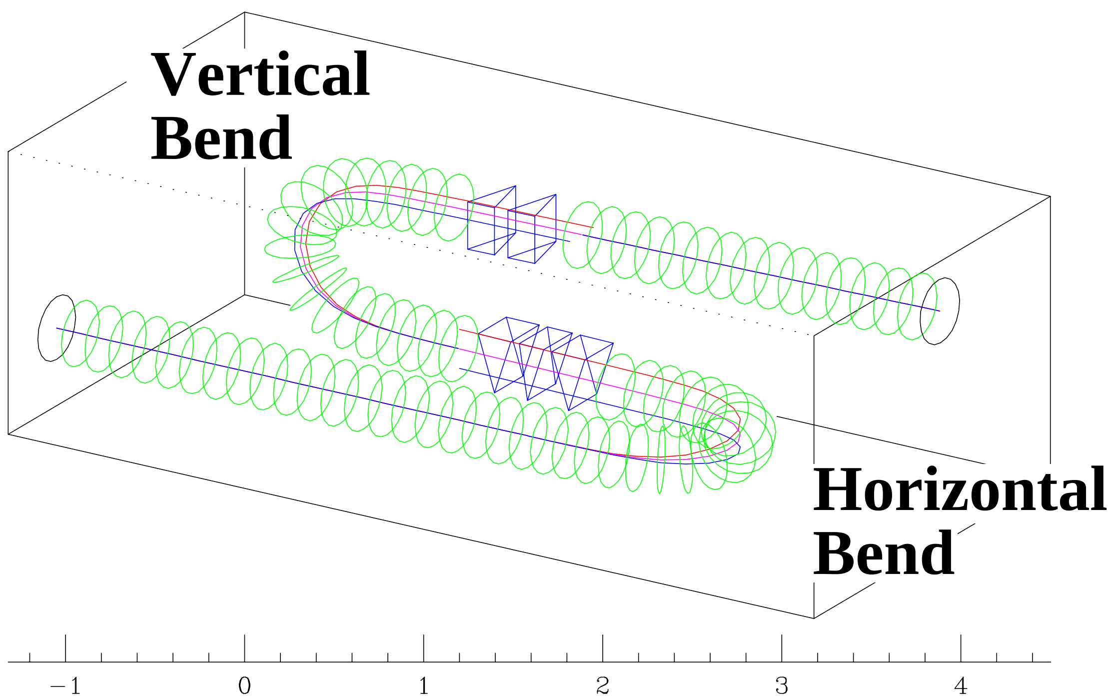
2. Very high surface fields (~ 90 MV/m) in conventional cavities −> clean structures + appropriate power source (>60 MW, 800 MHz Klystron).

- Vigorous R&D program being pursued ... *(BNL, FNAL, LBNL, Univ. of Mississippi)* ... building low power test cavities with foils, making high power breakdown & field emission tests, designing high field conventional cavity, and preparing a high power test facility (Lab G).

Controlling the Longitudinal Emittance

- **As a muon bunch travels down the transverse cooling channel its longitudinal emittance grows due to straggling in the liquid H_2 absorbers −> after ~20m the longitudinal emittance doubles**

- **Dispersion provided by bent solenoids (curvature drift effect)**

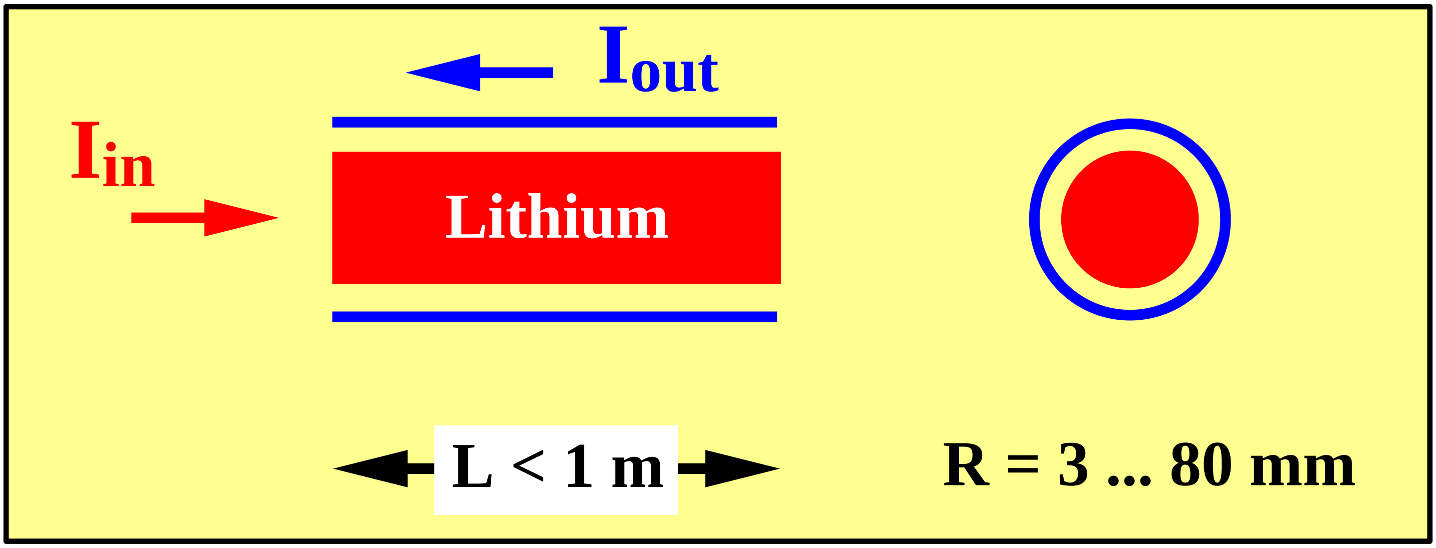


Scale (m)

Field	**3.5 Tesla**
Length	**8.5 m**
Beam tube diameter	**20 cm**
Minimum bend radius	**34 cm**

Lithium Lens Concept

- **Towards the end of the cooling channel, when the transverse emittances are small, to continue the fight against Coulomb scattering requires the strongest achievable radial focusing −> propose to use Lithium Lenses:**



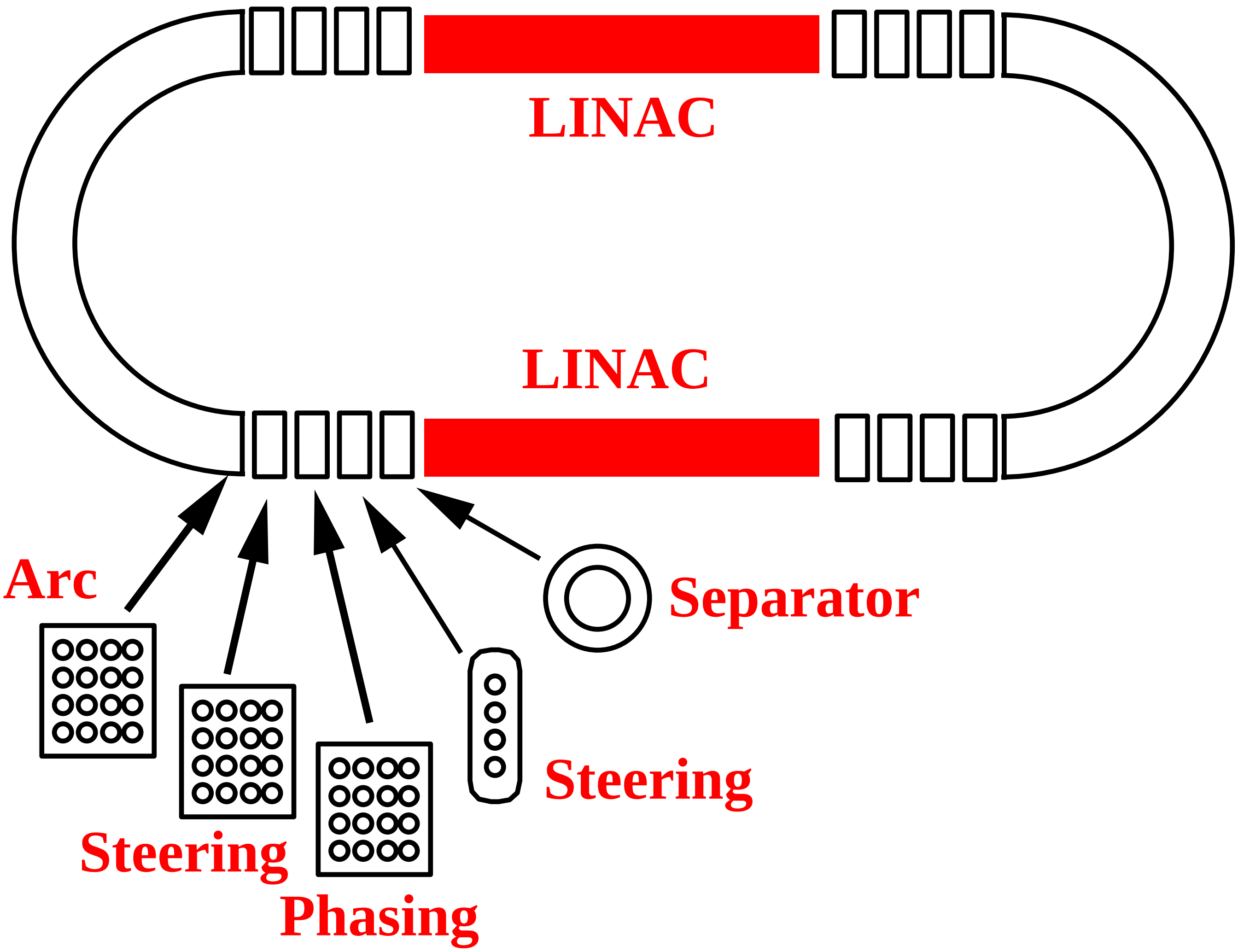
$$I(r) = I_0\left(\frac{r}{r_0}\right)^2 \qquad B_\phi(r) = B_0\left(\frac{r}{r_0}\right)$$

- **Lithium Lens provides Focusing + Cooling**
  - **Lens diameter matched to beam size**
  - **Focusing strength matched to emittance**
  - **I_{max} < 1 MA, B_{max} < 25 T**

- **Lithium rods with surface fields of 10 T were developed at Novosibirsk and have been operated as focusing elements at CERN and FNAL. We want to operate at up to 15 Hz. The resulting thermal load would melt a solid lens −> need liquid lithium lenses.**

Acceleration

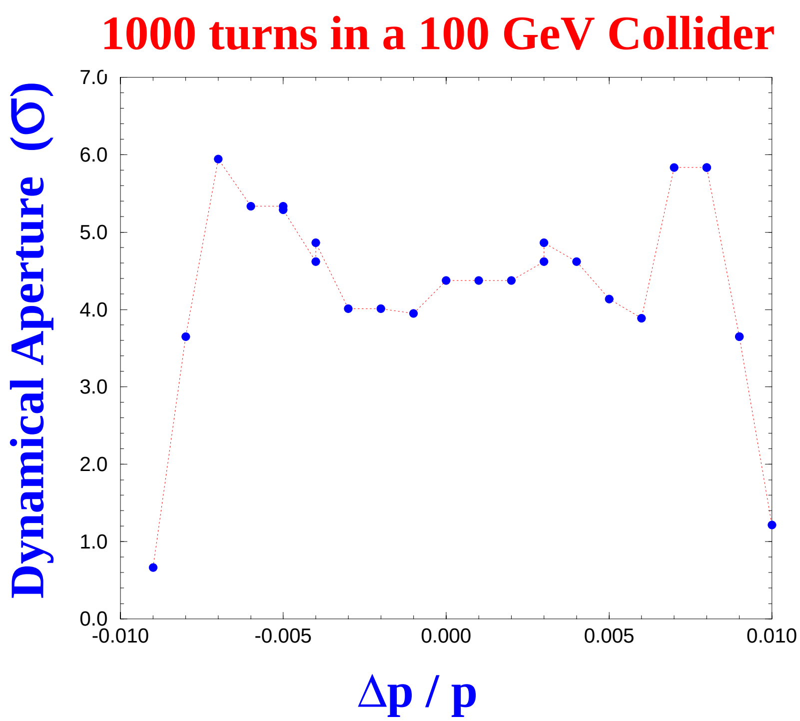
- Use a series of CBAF−like recirculating LINACs and/or rapid cycling synchrotrons.



	RLA 1	RLA 2	RLA 3	RLA 4
E(start) (GeV)	1.0	9.6	70	250
E(end) (GeV)	9.6	70	250	2000
No. Turns	9	11	12	16
Arc Length (m)	30	175	520	3500
Linac Length (m)	100	300	533	2800
Gradient (MV/m)	5	10	15	20
Decay Losses (%)	9.0	5.2	2.4	3.6

Collider

- **Highest average bending field needed to maximize number of revolutions before muons decay -> the muons would make about 1000 turns before muon decay has seriously depleted the luminosity.**
- **Need isochronous lattice to avoid excessive rf.**



Preliminary lattices have been designed for 0.1, 0.5, and 4 TeV colliders, and collimation schemes have been designed to remove halo muons.

- **Issues :**

  Polarization

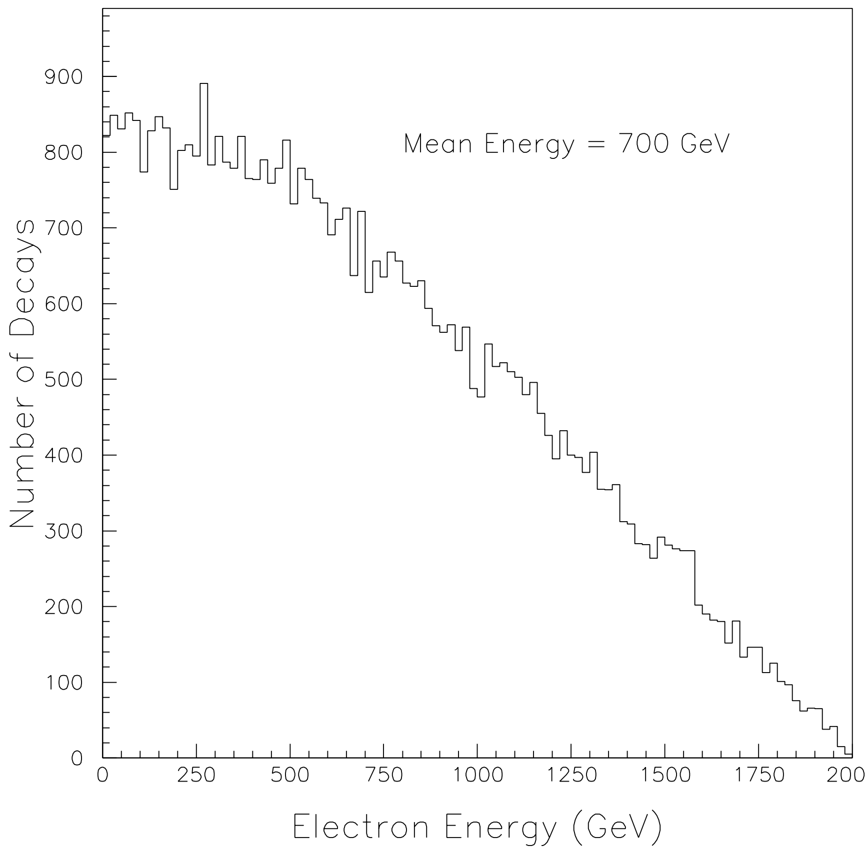
  Energy calibration

  Neutrino "radiation"

  Detector backgrounds

Muon Decay Backgrounds

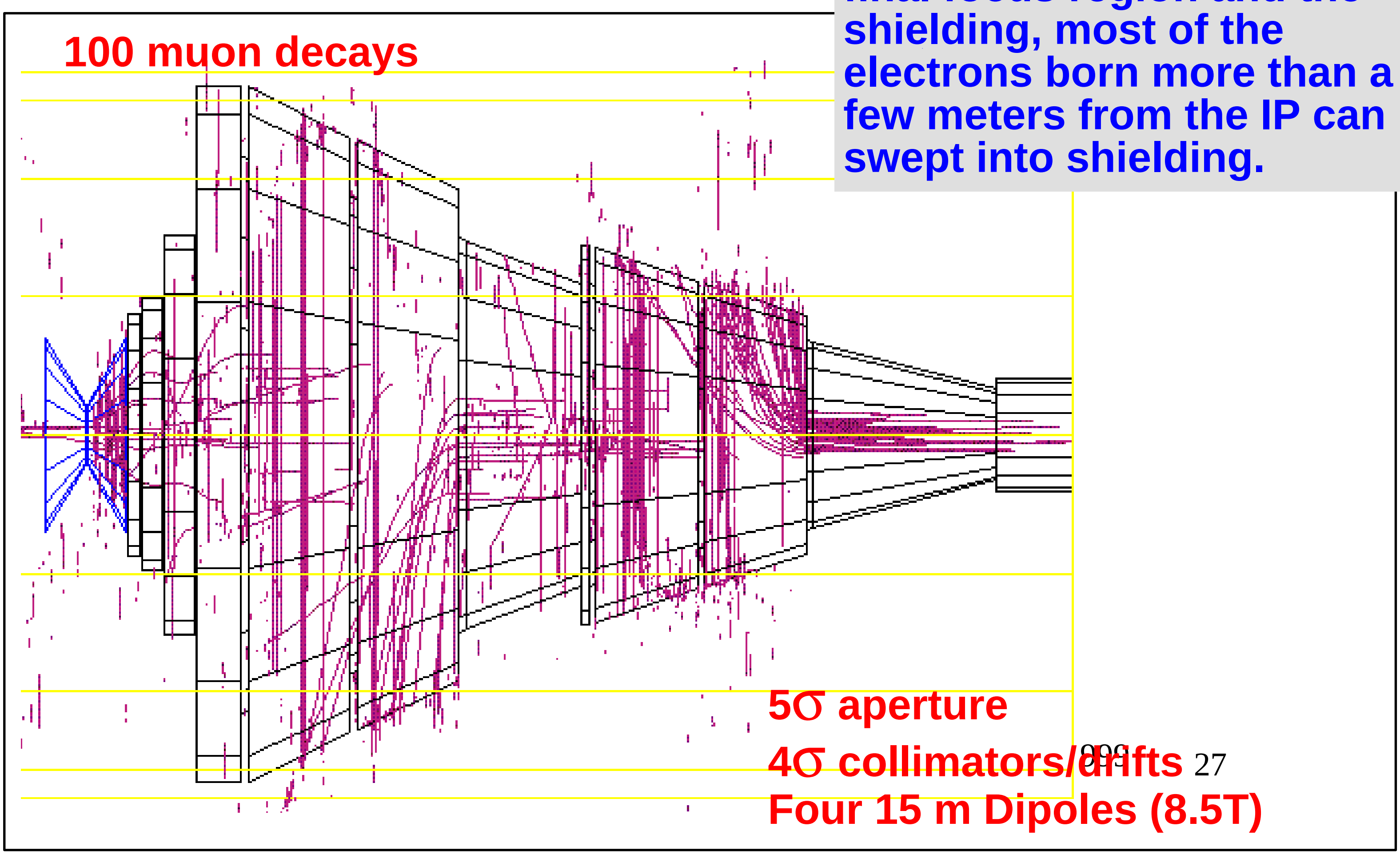
2 x 2 TeV



- 2×10^{12} muons/bunch
- 2×10^{5} decays / m
- Mean decay electron energy = 700 GeV

Electron decay angles are O(10) microradians. Therefore electrons born within a few meters of the IP do not contribute to backgrounds seen in the detector.

With careful design of the final focus region and the shielding, most of the electrons born more than a few meters from the IP can swept into shielding.



Background List

• Decay Backgrounds:

Two detailed complementary calculations have been performed for the high energy 2 x 2 TeV collider: GEANT calculation (I. Stumer, BNL), MARS calculation (N. Mokhov, FNAL). The assumed final focus system and shielding configurations assumed for the two calculations are similar in general, but the details are very different. The GEANT calculation has also been done for a 50 x 50 GeV Higgs factory.

Both the GEANT and MARS calculations track all particles through the final focus and 2 Tesla detector solenoidal fields and fully simulate:

- **Electron showers**
- **Synchrotron radiation**
- **Photonuclear interactions**
- **Bethe−Heitler muon pair production**

• Beam Halo:

Beam halo model and beam scraping design being developed. Initial scraper design reduced beam halo by x 1000. If halo originates from beam tails at > 3 σ then the halo will be of order 1 part in 10^6 or less .... which is thought to be OK. Further work is in progress.

• Beam−Beam Interactions:

Believed to be small compared with other backgrounds

GEANT RESULTS

Radial fluxes (cm^{-2} / crossing)

I. Stumer

radius (cm)	2 x 2 TeV *) γ	n	p	π	e	μ	50 x 50 GeV **) γ	n	p	π	e	μ
5	2700	120	.05	.9	2.3	1.7	4300	32	–	–	3.8	.15
10	750	110	.20	.4	–	0.7	1100	36	–	.24	.3	.07
15	350	100	.13	.4	–	0.4	480	75	–	.11	–	.03
20	210	100	.13	.3	–	0.1	270	98	–	.09	–	.007
50	70	120	.08	.05	–	.02	40	37	.05	.015	–	–
100	31	50	.04	.003	–	.008	9	18	.005	–	–	–
calo						.003	4	9	.02	–	–	–
muon						.0003						

*) Thresholds: $E_\gamma > 25$ keV, $E_n > 40$ keV, $E_p > 10$ MeV, $E_\pi > 10$ MeV.
**) Thresholds: $E_\gamma > 40$ keV, $E_n > 40$ keV, $E_p > 10$ MeV, $E_\pi > 10$ MeV.

Background fluxes are comparable or less than equivalent fluxes at LHC ($L = 10^{34}$ cm^{-2} s^{-1})

Hit Density in a Vertex Detector

- Consider a layer of Silicon at a radius of 10 cm at a 2 x 2 TeV Collider. The GEANT calculated fluxes ->

750 photons/cm^2	->	2.3 Hits/cm^2
110 neutrons/cm^2	->	0.1 Hits/cm^2
1.3 charged tracks/cm^2	->	1.3 Hits/cm^2
TOTAL		3.7 Hits/cm^2

-> 0.4% occupancy in 300 x 300 μm^2 pixels.

- This does not sound too bad. For comparison, SLD has about 40 Hits/cm^2 on their CCD inner layer.

- The numbers at 5 cm radius at a 2 x 2 TeV Collider are 13.2 Hits/cm^2 -> 1.3% occupancy.

- At a 100 GeV collider (I. Stumer) :

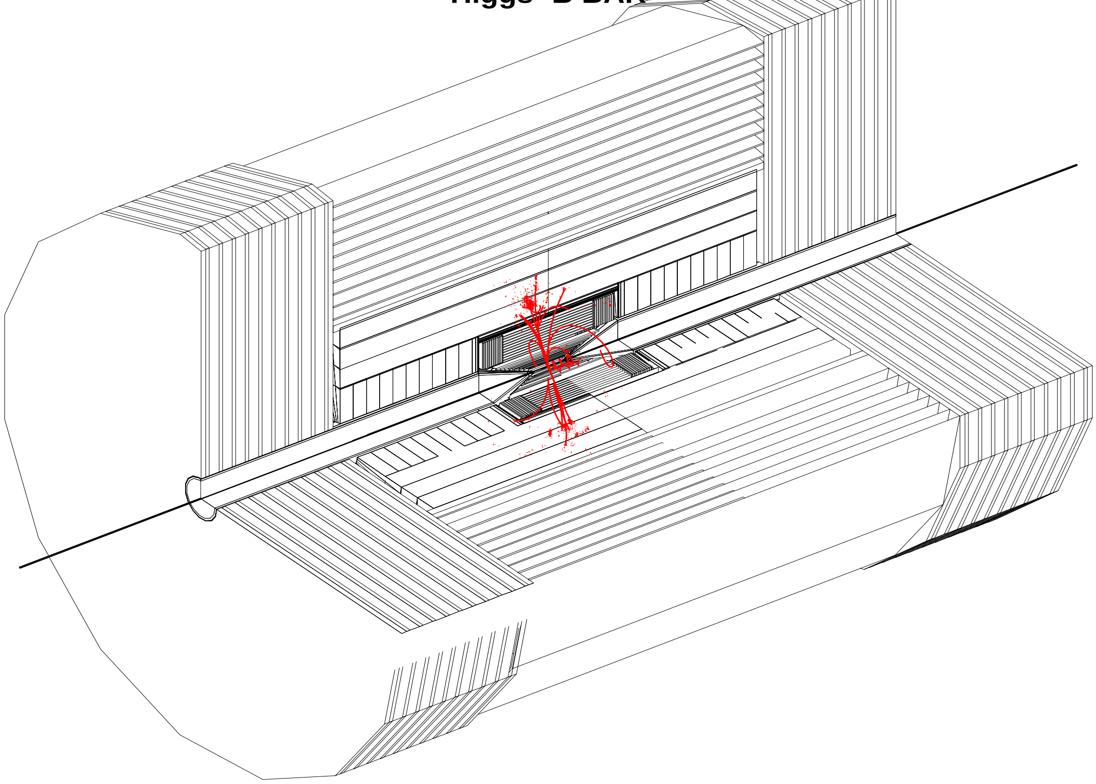
Radius (cm)	5	10	20	100
Photon hits/cm^2	26	6.6	1.6	0.06
Neutron hits/cm^2	0.06	0.08	0.2	0.04
Charged hits/cm^2	8	1.2	0.2	0.01
Total hits/cm^2	34	8	2	0.12
Pixel size (μm^2)	60x150	60x150	300x300	300x300
Occupancy (%)	0.14	0.02	0.04	0.002

Detector simulations

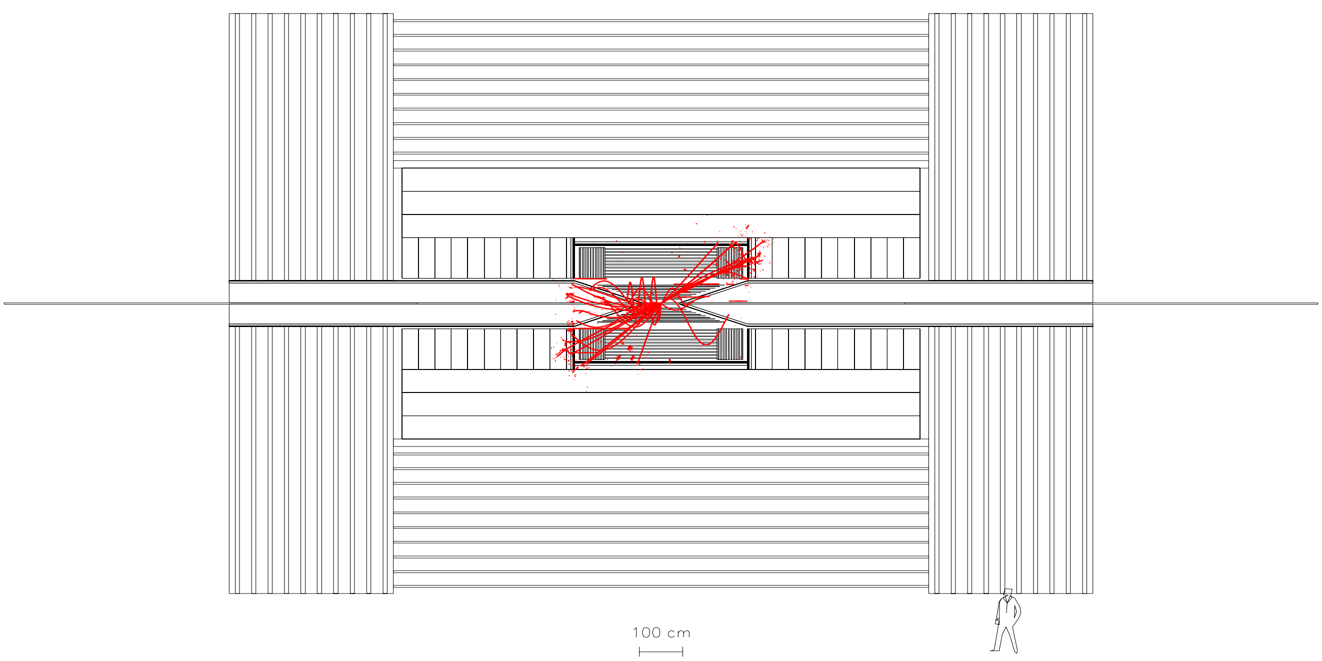
- Data driven geometry Geant 3.21 simulations. All constants in structured Ascii files. Easily upgradable to Geant4.
- Have simulated 1000 Higgs to bbar events. In the process of adding background and trying to estimate b tagging efficiency.
- Needs significant addition of manpower
- Proposal to DoE/NSF for University based Muon Collider fellowships

Mu_Geant pictures

Higgs- B BAR

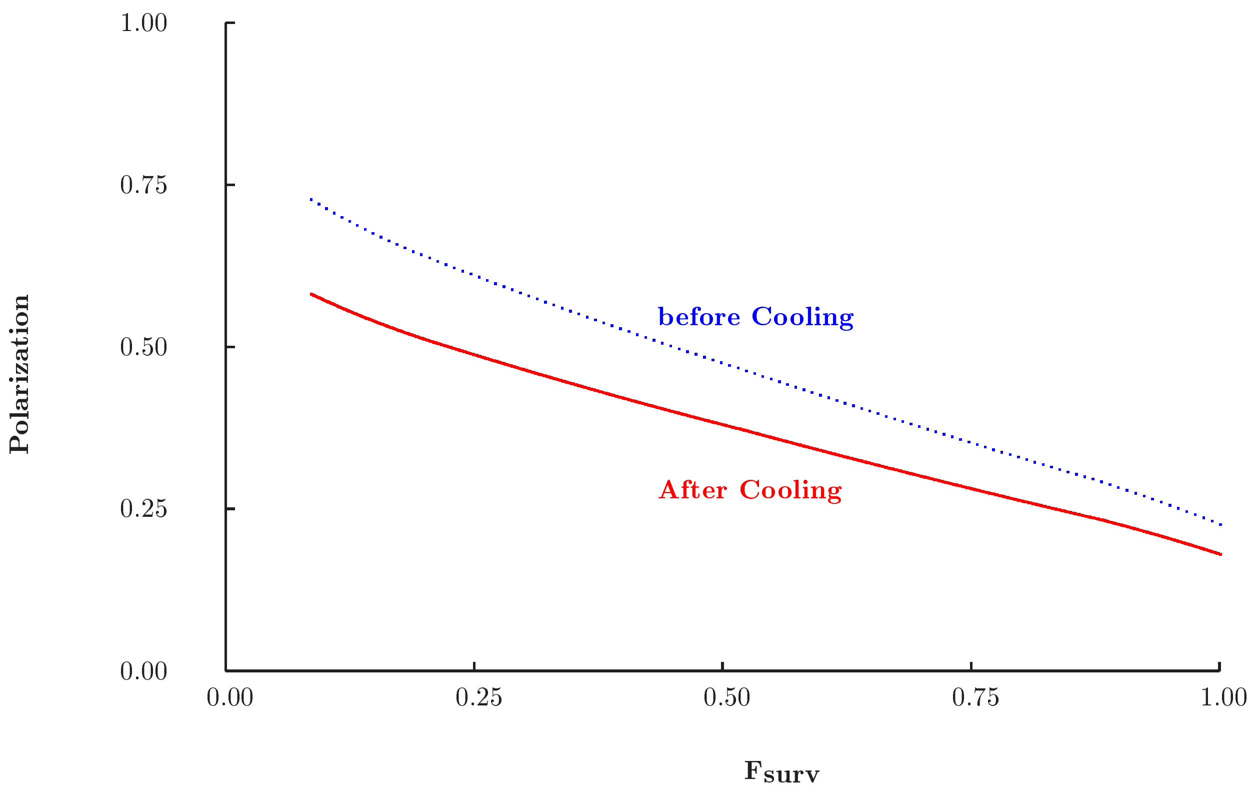


Higgs - B BAR



Muon Collider Physics

- Polarization of muons will play a crucial role in many physics areas.
- Both charges polarizable.



Calibrating the energy of the collider to 1E-6

Bargmann-Michel-Telegdi Equation

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{e}{m\gamma}((1+a\gamma)\vec{B}_{\neg} + (1+a)\vec{B}_{\Uparrow} - (a\gamma + \frac{\gamma}{1+\gamma})\vec{\beta} \times \frac{\vec{E}}{c})$$

$$\vec{\Omega} = \vec{\Omega}_{cyc}(1+a\gamma)$$

$$a = (g-2)/2$$

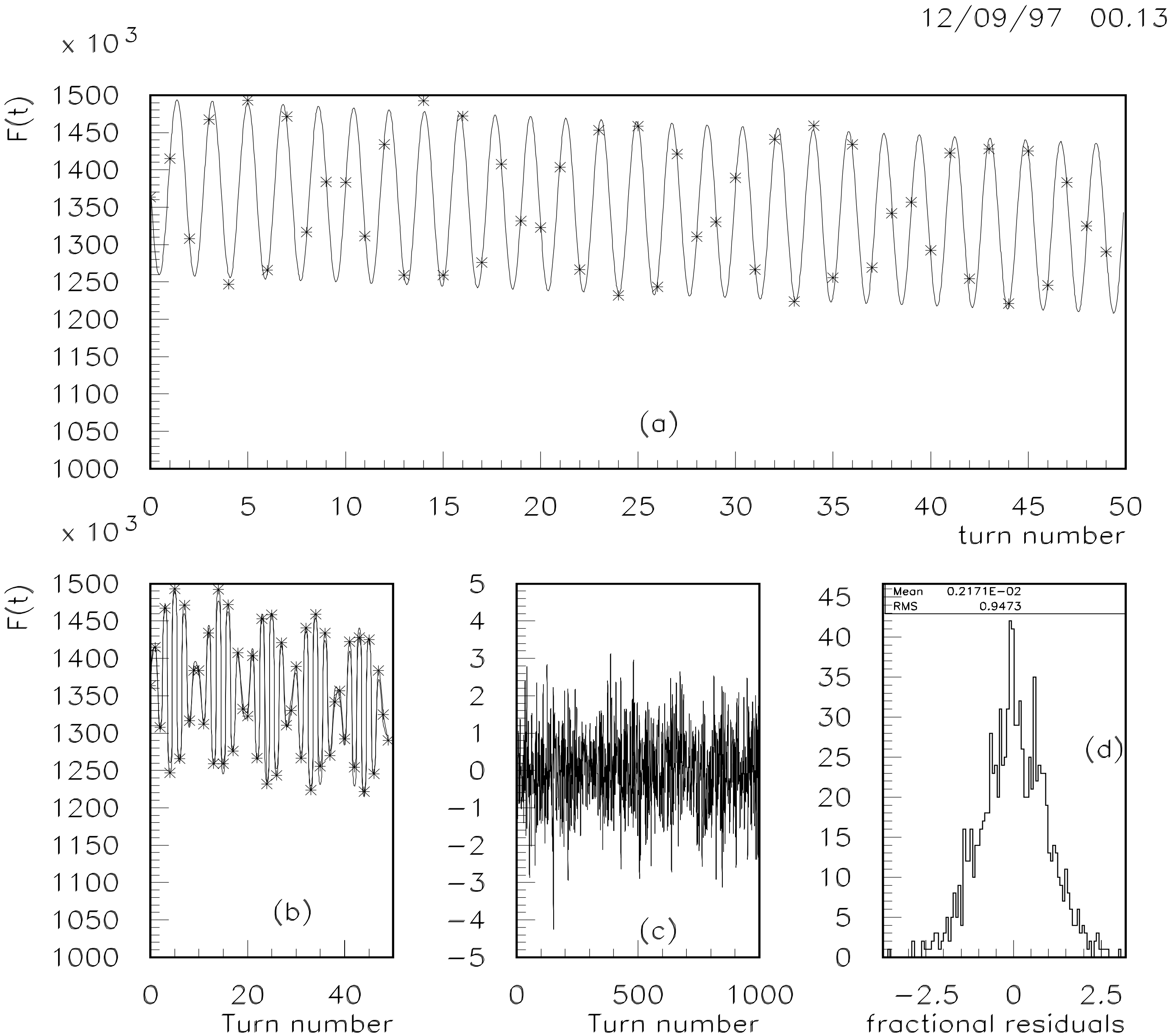
$B_{\neg}, B_{\Uparrow}$ are the components of magnetic field perpendicular and parallel particle direction

This equation controls the evolution of the spin vector $\vec{S}$. Polarization is the average of the spin vectors over the muon ensemble. Per revolution spin rotates by $a\gamma 2\pi$ radians more than momentum

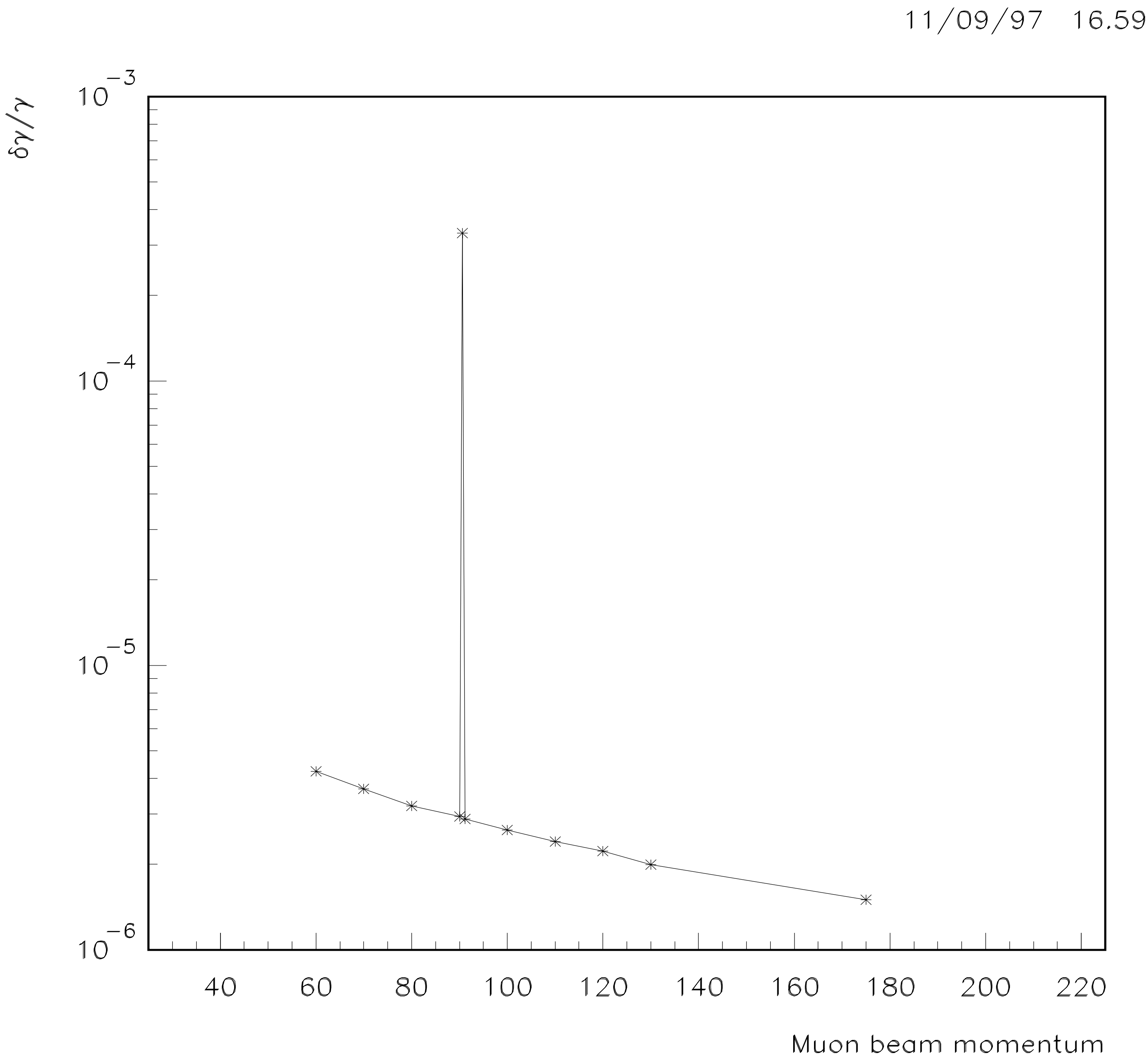
Method described in

R.Raja and A. Tollestrup, Phys. Rev. D58(1998)013005

Fit to 50 GeV μ^-, P=0.26
$\delta p/p$=0.03E-2



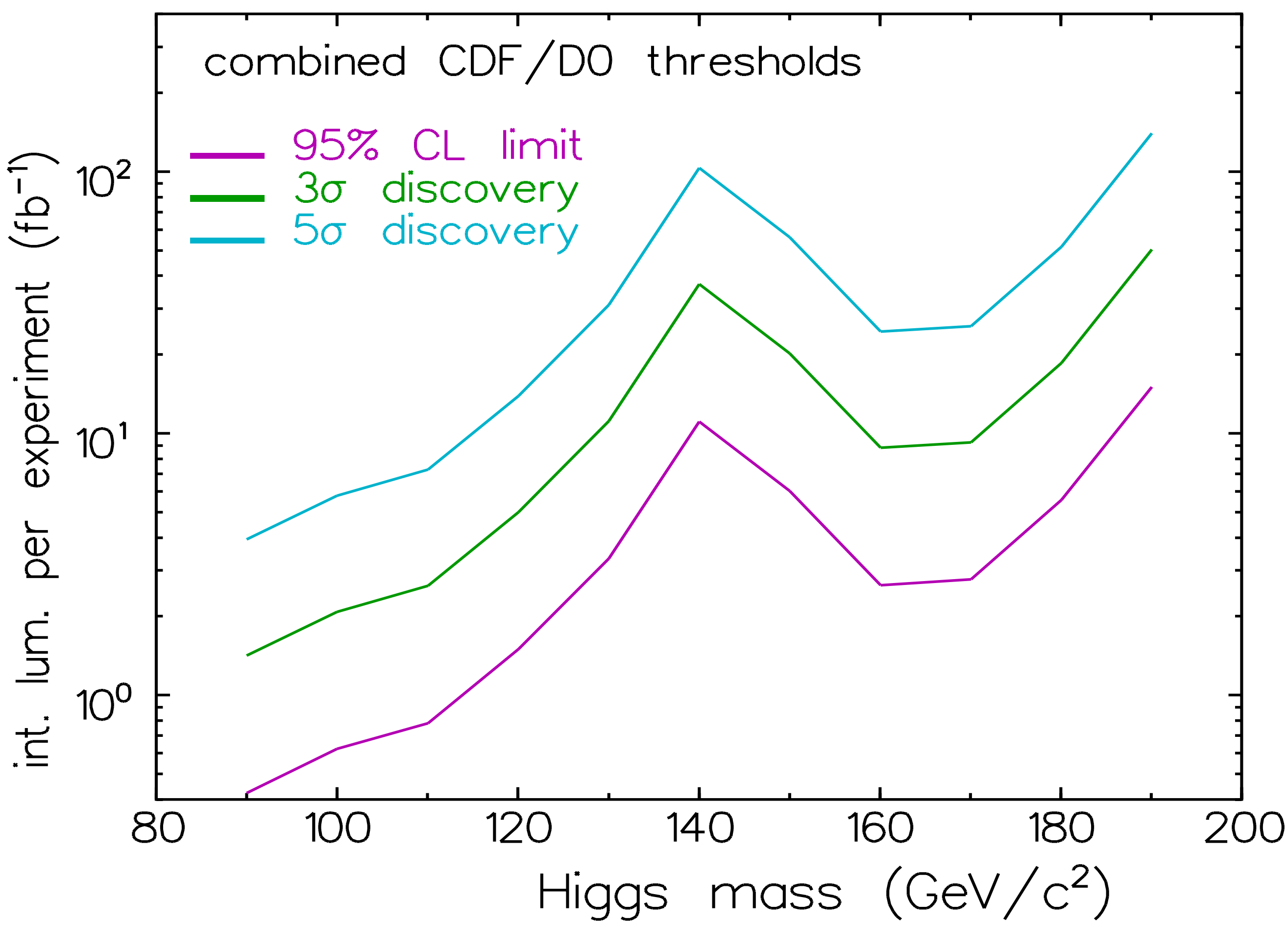
$\delta\gamma/\gamma$ vs muon beam momentum



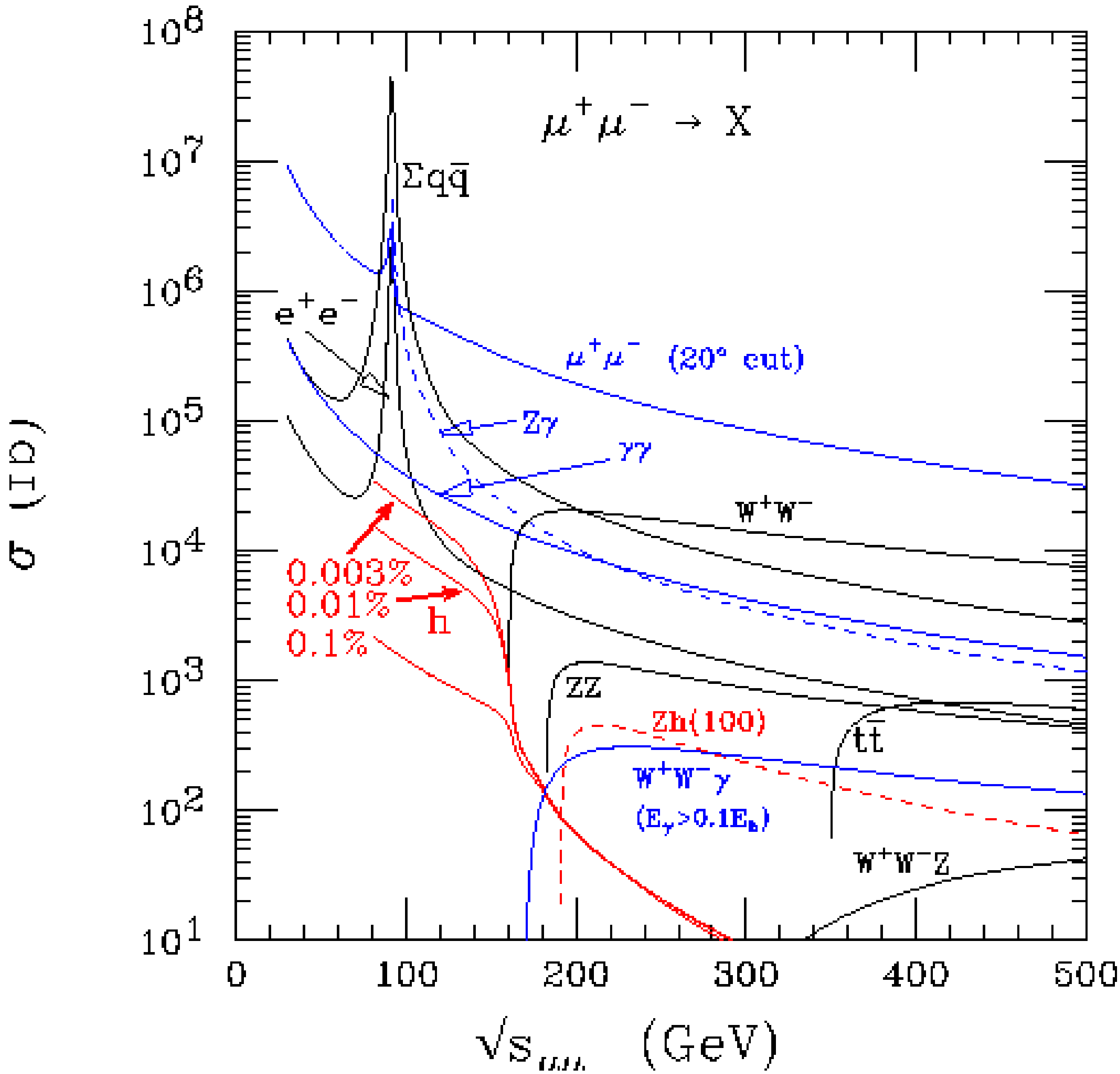
Tevatron Run III Standard model Higgs limits

Combined channel thresholds

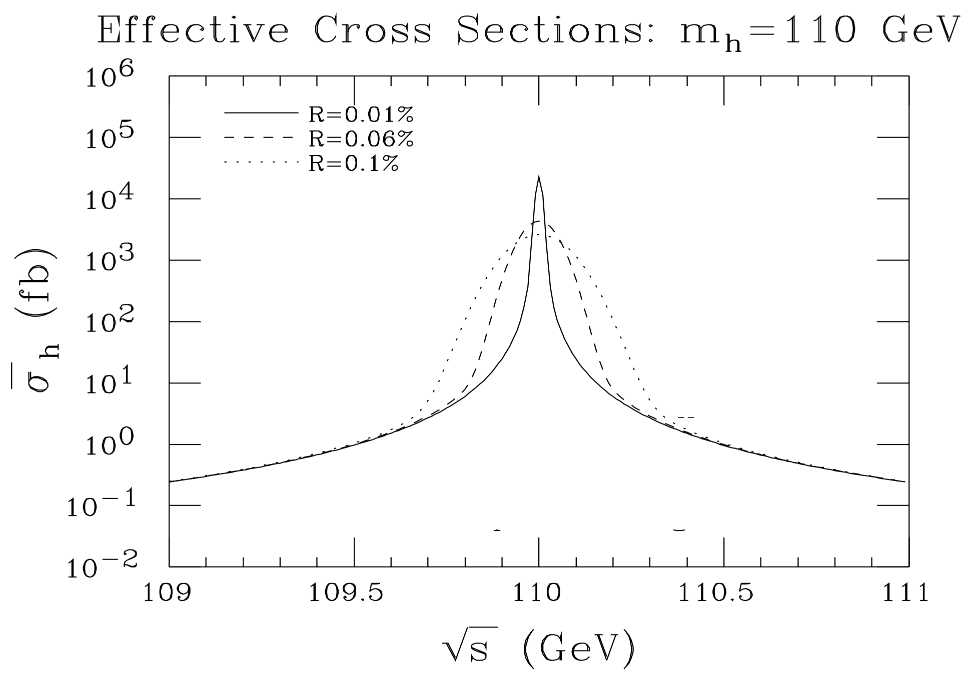
- → Gaussian approximation in combination
- → 30% better $m_{b\bar{b}}$ resolution than Run 1
- → Run 2 acceptance $\times$1.3 NN improvement
- → 10% systematic error on background
- → all except $\ell^{\pm}\ell^{\pm}jj$



Standard model cross sections at the first muon collider



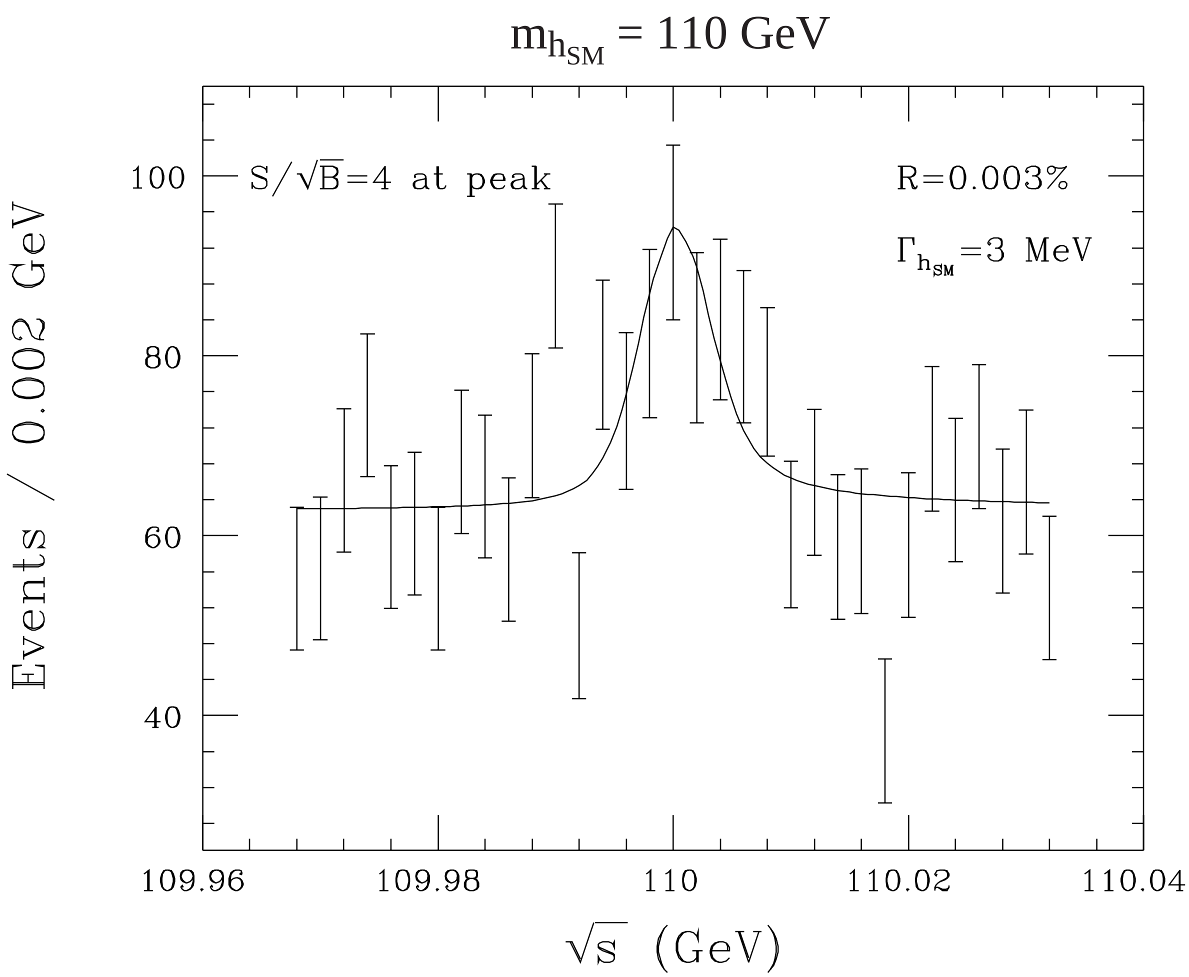
Scanning a light Higgs at the First Muon Collider



- Γ_h = 2-3 MeV if tan β = 1.8
- Γ_h = 2-800 MeV if tan β = 20
- 0.4fb-1 , will give the following measurement errors

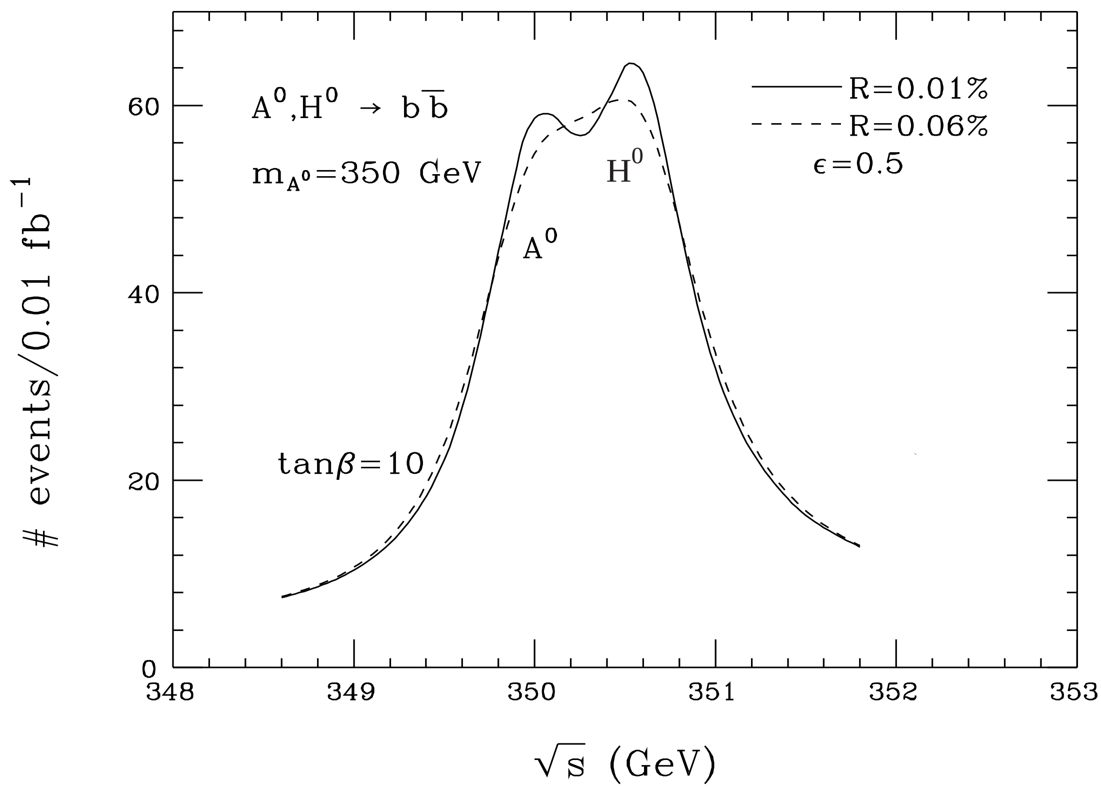
  Γ_h = 16%, σ.BF(bb)=1%, σ.BF(WW*)=5%
- r=BF(WW*)/BF(bb) is sensitive to m_{A0} for m_{A0}<500GeV.
- r_{MSSM}/r_{SM} = 0.3,0.5,0.8 for m_{A0}= 200,250,400 GeV

Scanning the Higgs peak using the muon collider



- 1 year of running at $L=1.5\times10^{31}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- $(0.15\mathrm{fb}^{-1})$/year to measure the Higgs mass to 1MeV

Resolving a degenerate H^0 and A^0 in MSSM using the muon collider



- H^0 and A^0 are broader. Γ~30MeV $m_{A0}<2m_t$, and Γ~3GeV for $m_{A0}>2m_t$. Can use broad-band collider.
- In the MSSM, $m_{A0} \sim m_{H0} \sim m_{H+} \sim m_{H-}$ for large m_{A0}.
- In this case only the muon collider s-channel scan can distinguish between the two nearly degenerate states.

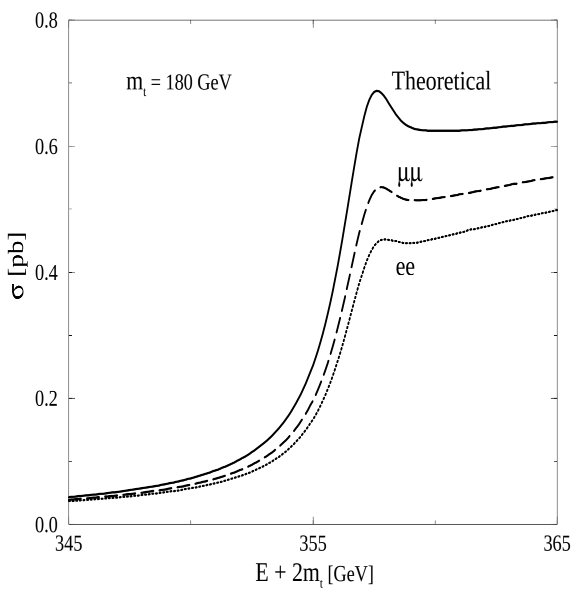
Threshold scans

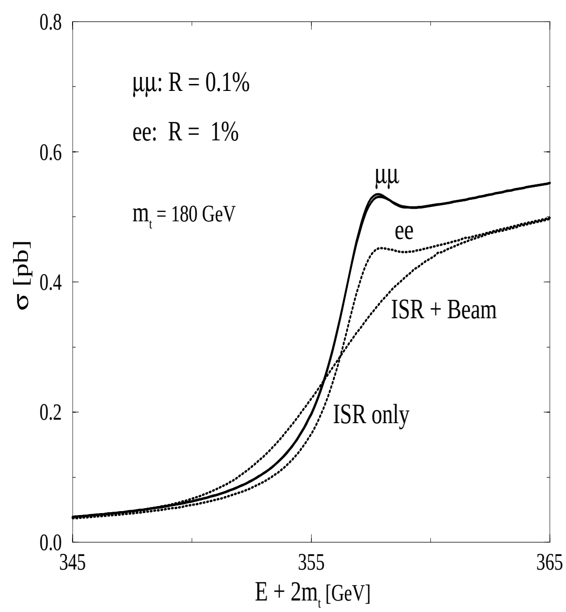
- With 10 fb^{-1} of luminosity devoted to a threshold scan cross-section, the following precisions on particle masses may be achievable.

$$\mu^+\mu^- \to W^+W^- --\Delta m_W = 20\,MeV$$

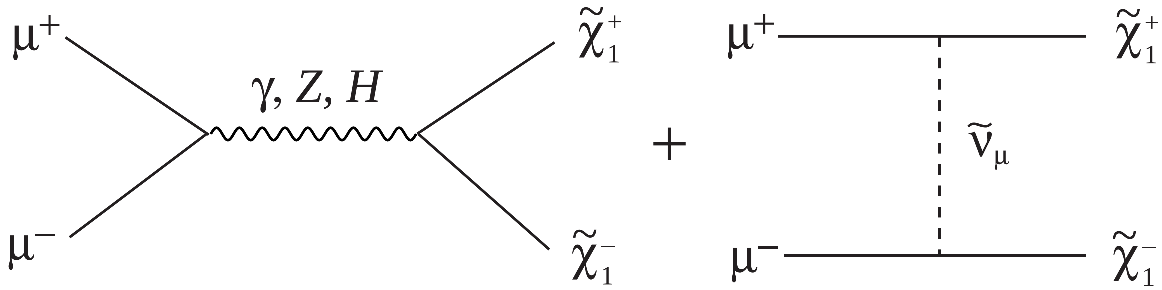
$$\mu^+\mu^- \to t^+t^- --\Delta m_t = 200\,MeV$$

$$\mu^+\mu^- \to Zh \quad --\Delta m_h = 140\,MeV$$

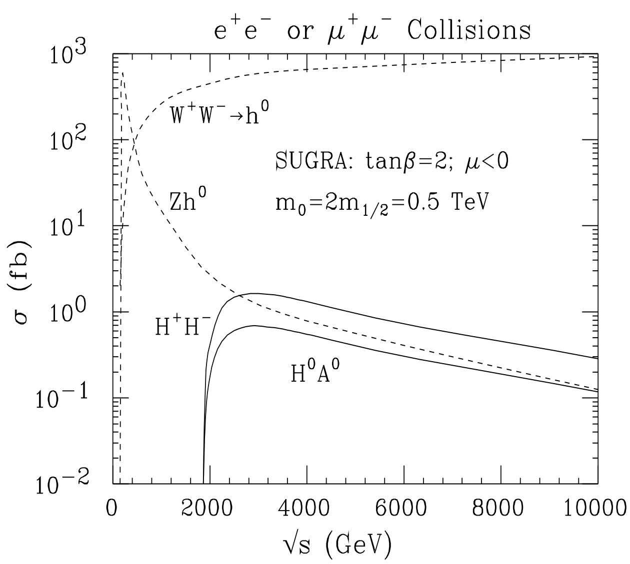


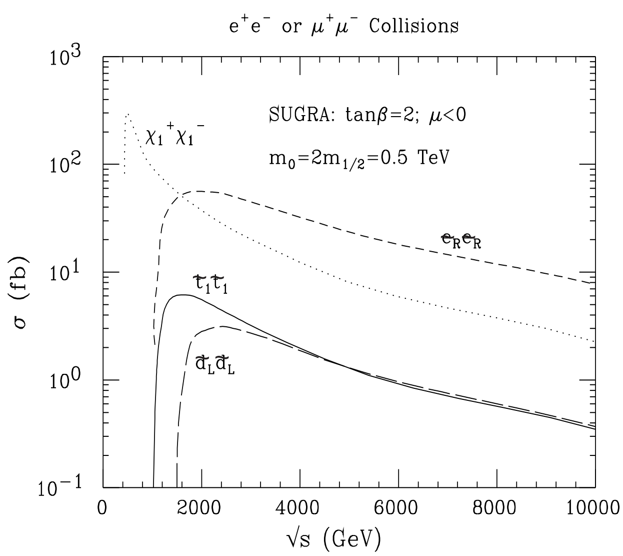


Susy production

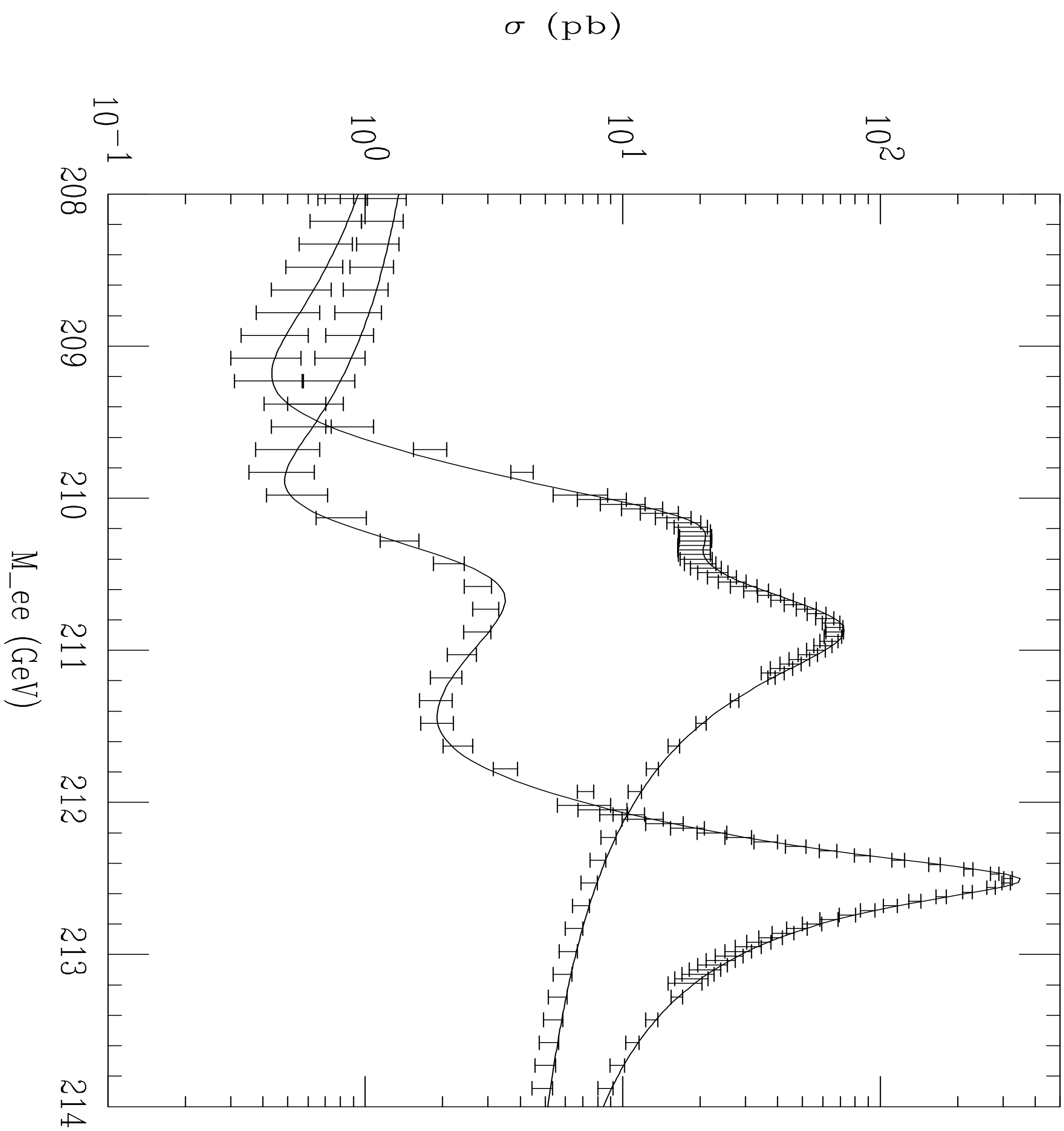


- 50fb^{-1} and momentum resolution =0.1% and two scan points can lead to mass determination of chargino to 35(45) MeV for a chargino mass of 100 GeV and a sneutrino mass of 500 (300) GeV; mass errors of 150(300)MeV for chargino mass of 200 GeV and a sneutrino mass of 500(300)GeV.
- Heavy Susy Scalar pair production is P-Wave suppressed. For masses of 1TeV, collider energy of 3-4 TeV CMS is needed. Muon Collider would do the job.





Technicolor s channel production-ρ_T ω_T interference



- Fine energy resolution of muon collider an asset. (Eichten et al-PRL80(98)5489)

Neutrino Beams from Muon Decay

- **The idea of exploiting muon decays to produce a neutrino beam has been discussed many times in the literature.**

- **Pure flavor content with large ν_e component:**

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	50% ν_e ($\bar{\nu}_\mu$)
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	50% $\bar{\nu}_e$ (ν_μ)

- **Precisely known fluxes and kinematics:**

In the $\mu^\pm$ rest−frame, the distribution of neutrinos from muon decay is given by:

$$\nu_\mu : \quad \frac{dn}{dx\,d\Omega} = \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)P\cos\theta\right]$$

$$\nu_e : \quad \frac{dn}{dx\,d\Omega} = \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)P\cos\theta\right]$$

where $x = 2E_\nu/m_\mu$, θ is the angle between the neutrino and the muon spin, and P is the muon polarization.

Basic Idea

- **To avoid an impractically long decay channel (note: $\tau_\mu \sim 100\ \tau_\pi$) use a storage ring with a long straight section.**

- **To date the problem has been that muon sources have not been sufficiently intense to make a muon storage ring neutrino source really interesting.**

- **Front end of a muon collider (Example scenario) :**

Proton Driver: **1.5 x 10^{15} protons/sec @ 16 GeV (5 x 10^{13} protons/bunch x 2 bunches x 15 Hz)**

Pion Production: **3 x 10^{13} π^+ (π^-) per proton bunch**

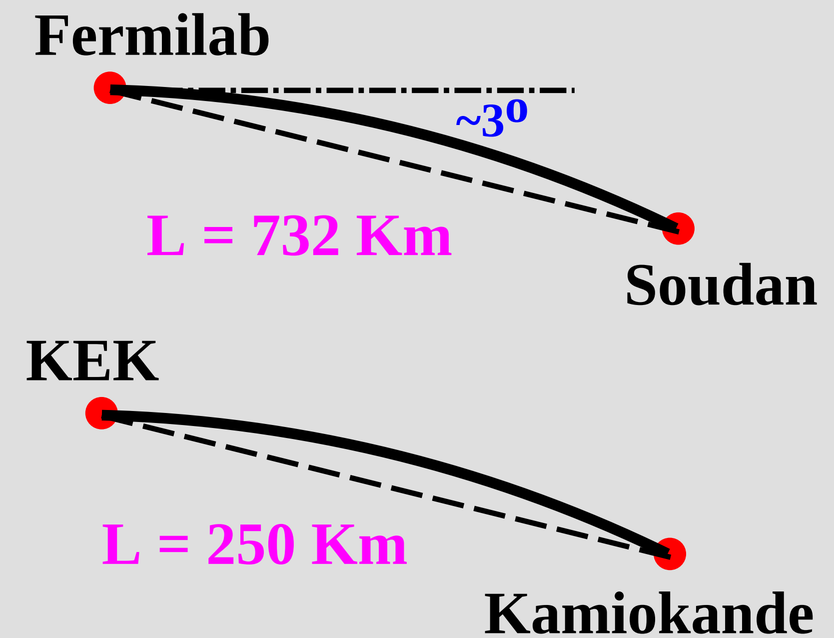
Muon Source: **1 x 10^{13} μ^+ (μ^-) per proton bunch**

Cold Muon Source: **7.5 x 10^{20} μ^+ (μ^-) per year (5 x 10^{12} muons/bunch x 2 bunches x 15 Hz)**

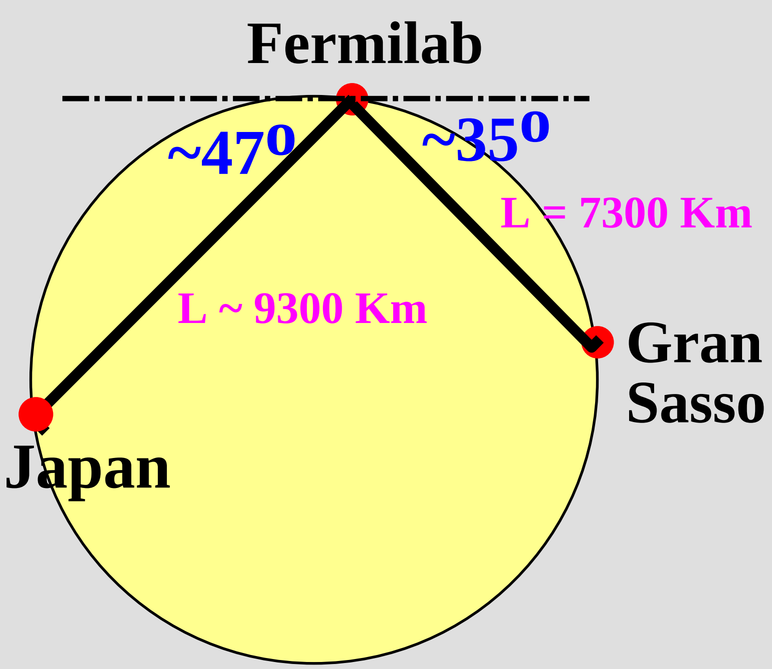
A millimole of muons/year ... & they all decay −> a few x 10^{20} – 10^{21} ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ per year !

- **It has been realized that a muon collider muon source is sufficiently intense to fire a 10−20 GeV ν beam through the earth & detect hundreds of neutrino interactions / yr** *(S. Geer, PRD 57,6989 (1998))*

Long Baseline Options



E_ν (GeV)	L/E (Km/GeV) FNAL−Soudan	L/E (Km/GeV) KEK−Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3

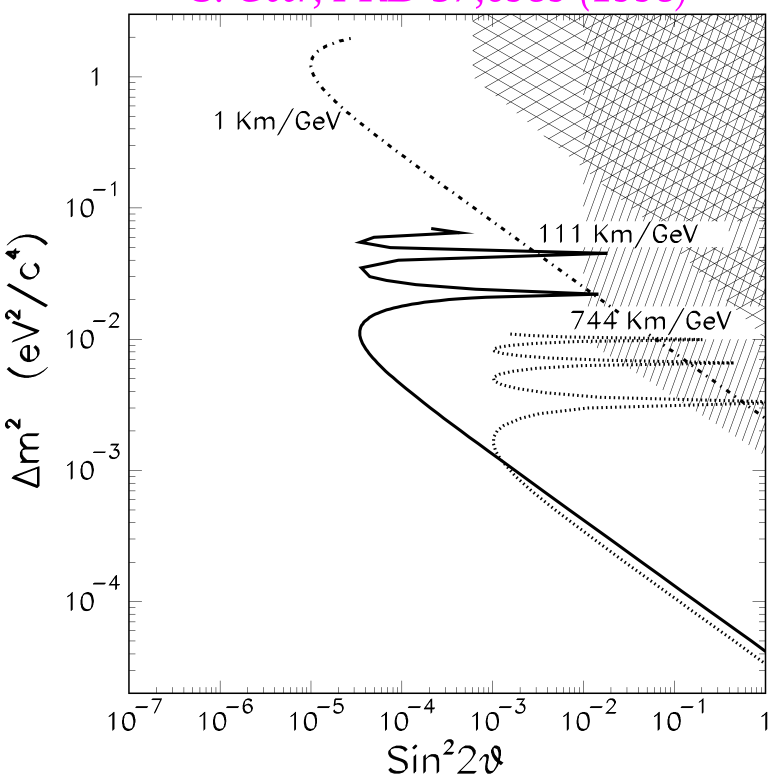


E_ν (GeV)	L/E (Km/GeV) Gran S.	L/E (Km/GeV) Japan
10	~730	~930
20	~370	~470
30	~240	~310
40	~180	~230
50	~150	~190

Sensitivity to Δm^2 & $\sin^2 2\theta$

Unpolarized μ^+ beam, 1 year run

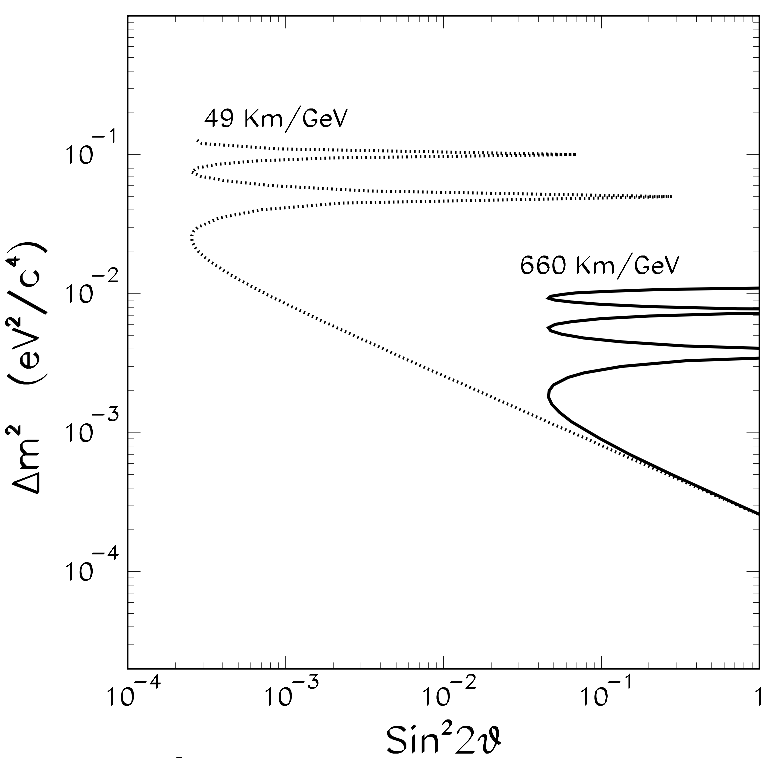
S. Geer, PRD 57,6989 (1998)



$\nu_e - \nu_\mu$: Search for wrong−sign muons

Hatched: MINOS − 2 yrs
Cross−Hatched: MiniBooNe

p_μ (GeV)	m_{DET} (KT)	L (km)	$< L/E_\nu >$ (km/GeV)
20	10	10000	744
10	10	732	111
1.5	0.02	1	1



$\nu_e - \nu_\tau$: Search for wrong−sign muons

p_μ (GeV)	m_{DET} (KT)	L (km)	$< L/E_\nu >$ (km/GeV)
20	10	10000	660
20	10	732	49

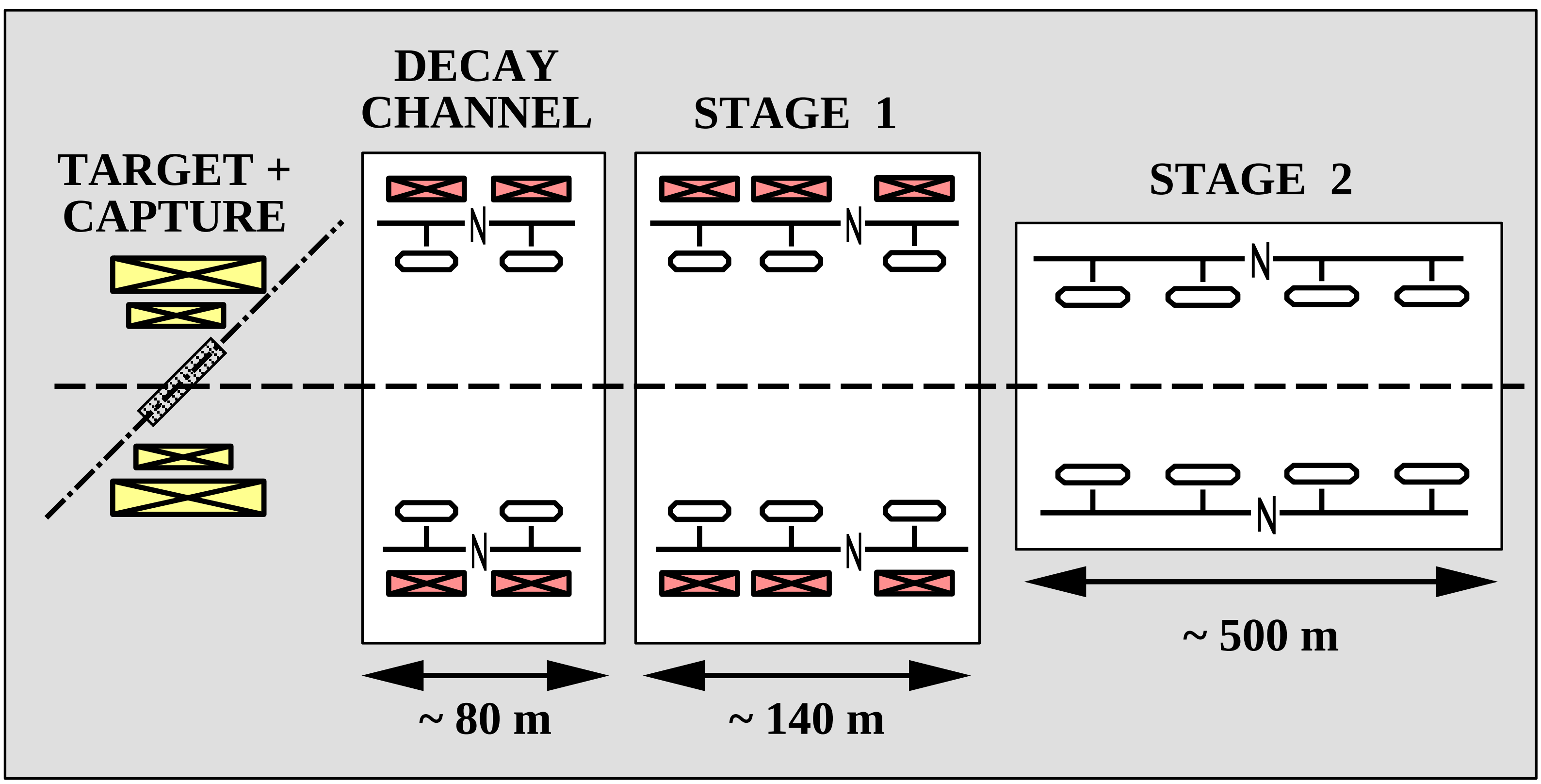
Recent Work on a Capture, Acceleration, & Muon Storage Ring Scenario − (1)

B. Autin, S. Geer, C. Johnstone & D. Neuffer

- **Dont need all the muons in a single bunch −>**

STAGE 1: Capture & begin acceleration with 800 MHz rf , V_{rf} = 15 MV/m, ϕ_S = 30^o, linac length = 140m.

STAGE 2: Continue acceleration up to 10 GeV with 800 MHz rf , V_{rf} = 20 MV/m, ϕ_S = 60^o, linac length = 500m.



Updated Neutrino Fluxes

B. Autin, S. Geer, C. Johnstone & D. Neuffer

Unpolarized 10 GeV muons stored in a ring pointing at an experiment at L = 732 Km (FNAL − Soudan):

Preliminary

- $\phi_{\bar{\nu}_e} = \phi_{\nu_\mu} = 3 \times 10^{12} / m^2 / yr$
- **Flux loss at L = 732 Km due to beam divergence in straight section is ~10% ... with beam profile measurements the systematic uncertainty on this should be acceptable.**

Note: This flux is about 3 x higher than obtained in *S. Geer, PRD 57, 6989 (1998)* **which used a different (but equally valid) front−end scenario. Changes are due to:**

(i) use both proton bunches per cycle (not just 1 out of 2),

(ii) updated estimate of muon rate out of decay channel (*Neuffer & Van Ginneken*),

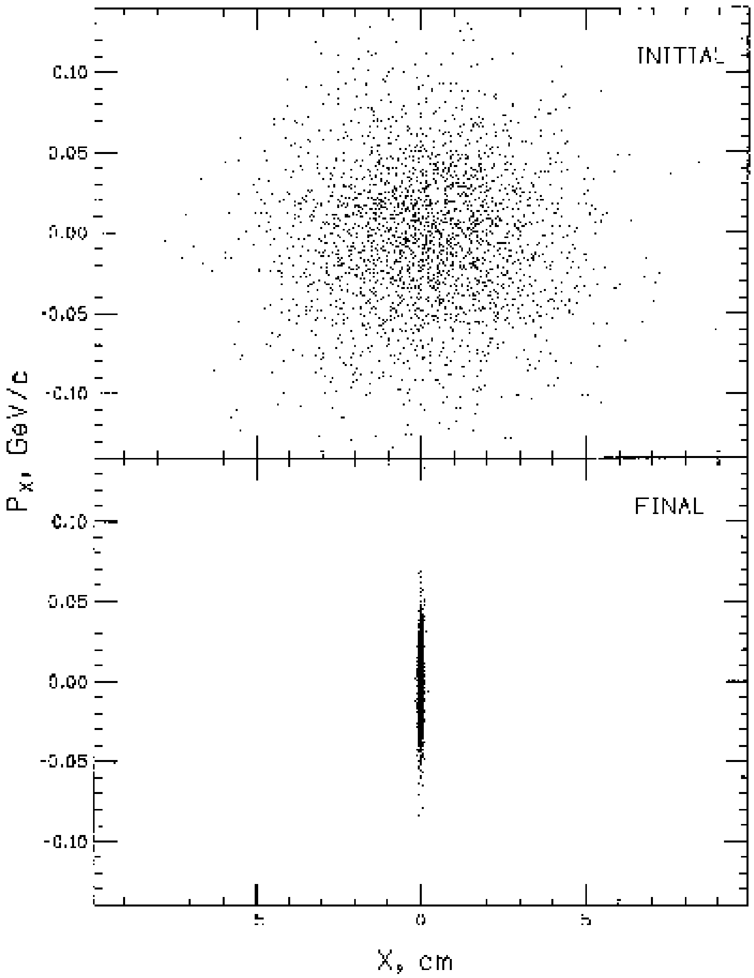
(iii) 50% longer straight section in storage ring,

(iv) additional factor of 0.6 loss due to 800 MHz capture efficiency.

Conclusions

- The muon collider is a concept worth investigating further
- Not all problems are solved, i's dotted and t's crossed. It is possible to take a critical look at any one component and immediately see further problems.
- It is by this process of critical examination that problems have been solved and the examiners become proponents.
- Promise of physics on the way to the collider.
- Collider promises unique access to s-channel Higgs and higher energies.

Lithium Lens Simulation Results



Toy simulations of a complete Lithium lens cooling system (*D. Neuffer, V. Balbakov*) −> idea of what is needed.

More complete simulations of a 2−lens system at end of channel (*P. Spentazouris*) −> works with unrealistic RF parameters.

Needs optimization to see if a lens system will work.

Needs new ideas to combine Li lens system with an emittance exchange system.

Liquid Lithium Lens R&D

- **Novosibirsk−FNAL contract exists to develop a 15 cm long liquid lithium lens for antiproton collection (r = 1 cm, surface field = 13 T, rep. rate = 0.5 Hz).**
  - **Lens designed. Status Review Feb. 14th, 1999**
  - **CY99: Build lens.**
  - **CY00: Test lens (10^6 pulses) & deliver to FNAL.**
- **Want to extend Lithium lens R&D to develop longer lenses (< 1m) with highest practical surface fields (up to 25 T) that can operate at 15 Hz.**

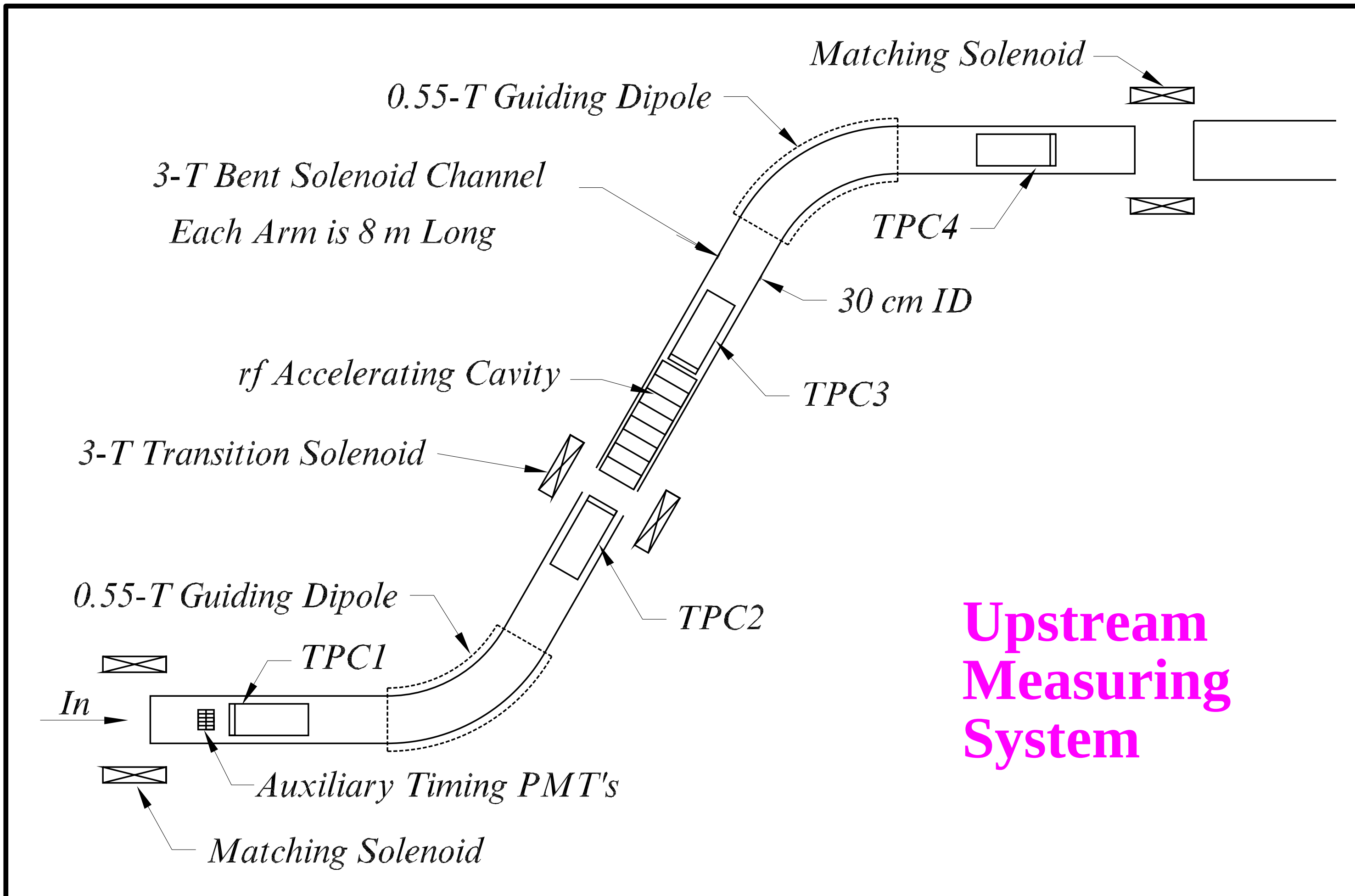
The Muon Cooling Challenge

- Note that an ionization cooling channel consists of an ~ 600 m long LINAC giving ~6 GeV of reacceleration, with the LINAC filled with material !
- The challenge is to find a realistic scheme that can provide within O(2 μs) a cooling factor of ~10^6 without loosing nearly all of the beam.
- –> MUCOOL Collaboration:

  - Develop Special RF Modules giving high peak accelerating gradients.
  - Design, build, & test an Alternating Solenoid Transverse Cooling Section.
  - Design, build, & test a Wedge "Energy Cooling" Stage.
  - Develop Long Liquid Lithium Lenses with a high surface field.
  - Build short cooling sections and test their performance in a low energy muon beam.

Upstream Instrumentation

(BNL, FNAL, Princeton, Mississippi,UCLA)



- **Auxiliary timing device**
- **TPC 1 –> helix before first bend**
- **Bent Solenoid**
- **TPC 2 –> helix after first bend**

First Momentum Measeurment

- **rf accelerating cavity**

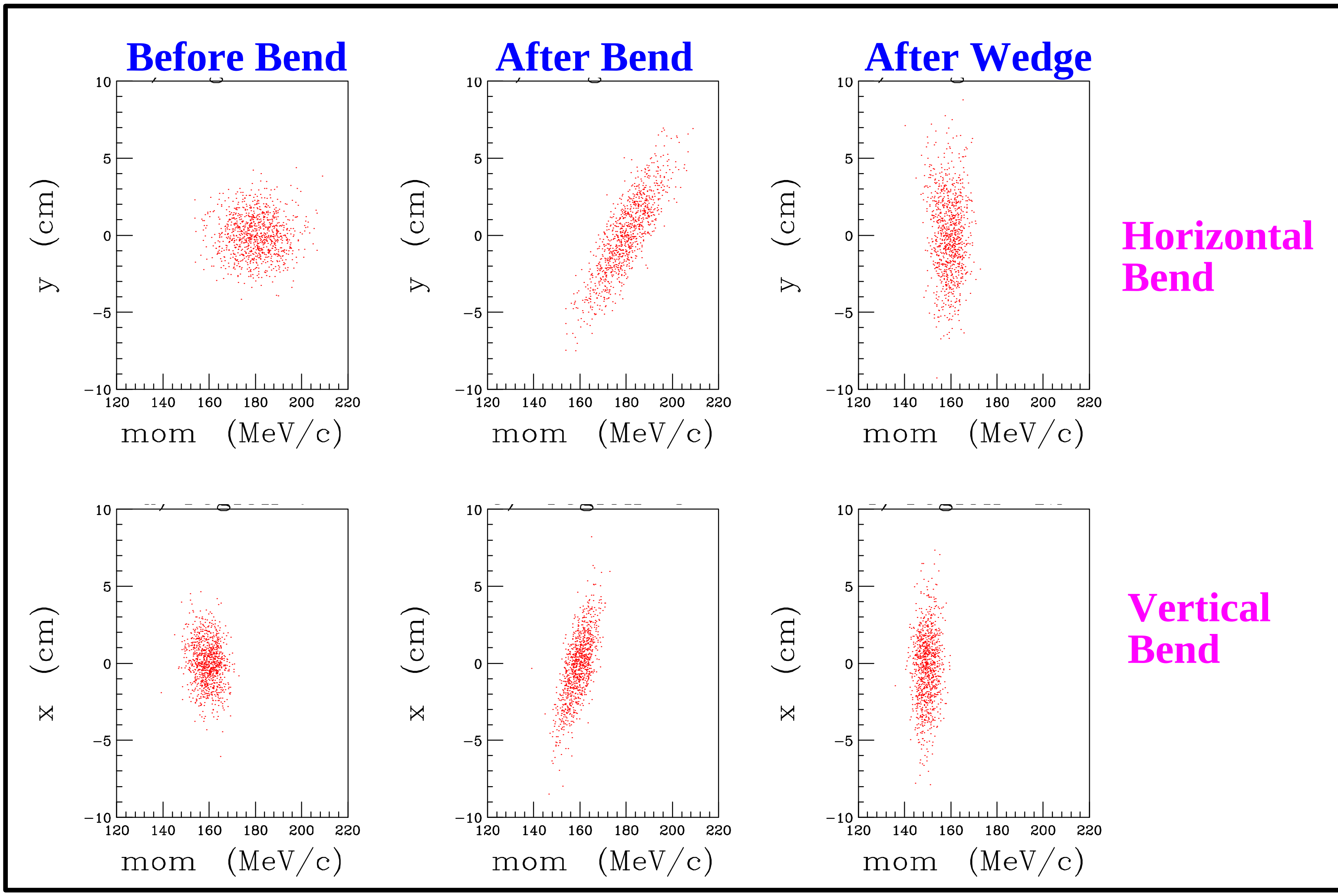
rf

- **TPC 3 –> helix before second bend**
- **Bent Solenoid**
- **TPC 4 –> helix after second bend**

Second Momentum Measeurment

Emittance Exchange Simulation Results

- Time coordinate not yet simulated. Needs more design & simulation work before we know if a realistic solution is feasible.



Simulation Results

	initial	final	factor
σ_p (MeV/c)	9.26	3.35	0.36
Av. Momentum (MeV/c)	180	150	0.83
Transverse size (cm)	1.33	2.26	1.70
p_T (MeV/c)	6.84	7.84	1.15
Trans. Emittance (π m mrad)	870	1694	1.37

Detectors and backgrounds

- Discuss background sources due to decay of muons in beam pipe
  - » Electron showers
    - Photons
    - Bethe Heitler Muons (Problem at higher energies)
    - Neutrons produced by Giant dipole resonances in nucleii by low energy photons
    - Synchrotron radiation
  - » Halo muons
    - Handled by scraping

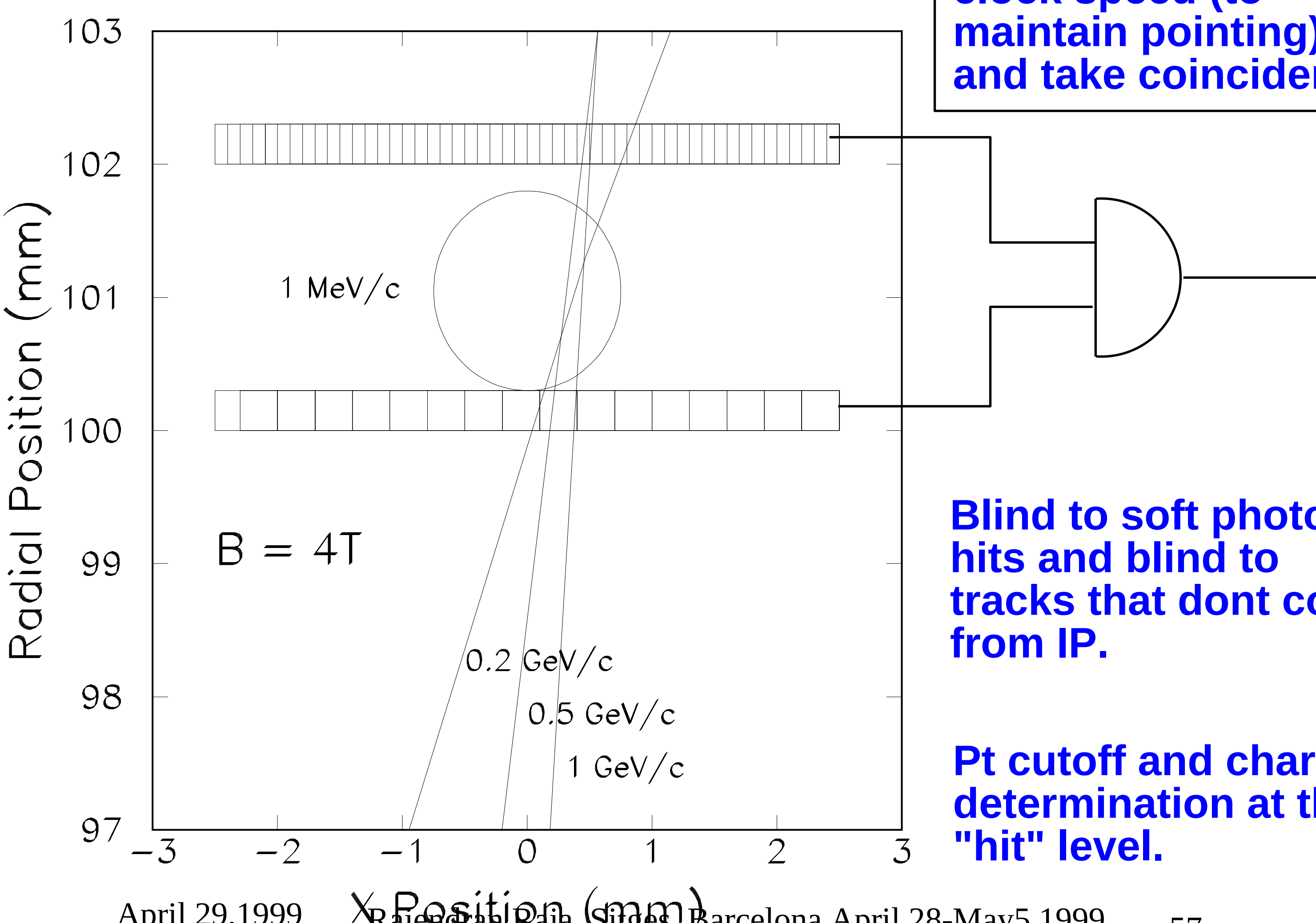
Pixel Microtelescope

Steve Geer
Jay Chapman

FERMILAB−CONF−96−375

- Most of the background hits in a silicon vertex detector close to the muon collider IP arise from very low energy (~ 1 MeV) photon interactions.
- At Snowmass we thought of a possible way of screening out these background hits to facilitate:
  - Getting the first layer at the smallest viable radius
  - Developing a track trigger

Clock two layers out at variable clock speed (to maintain pointing) and take coincidence.



Blind to soft photon hits and blind to tracks that dont come from IP.

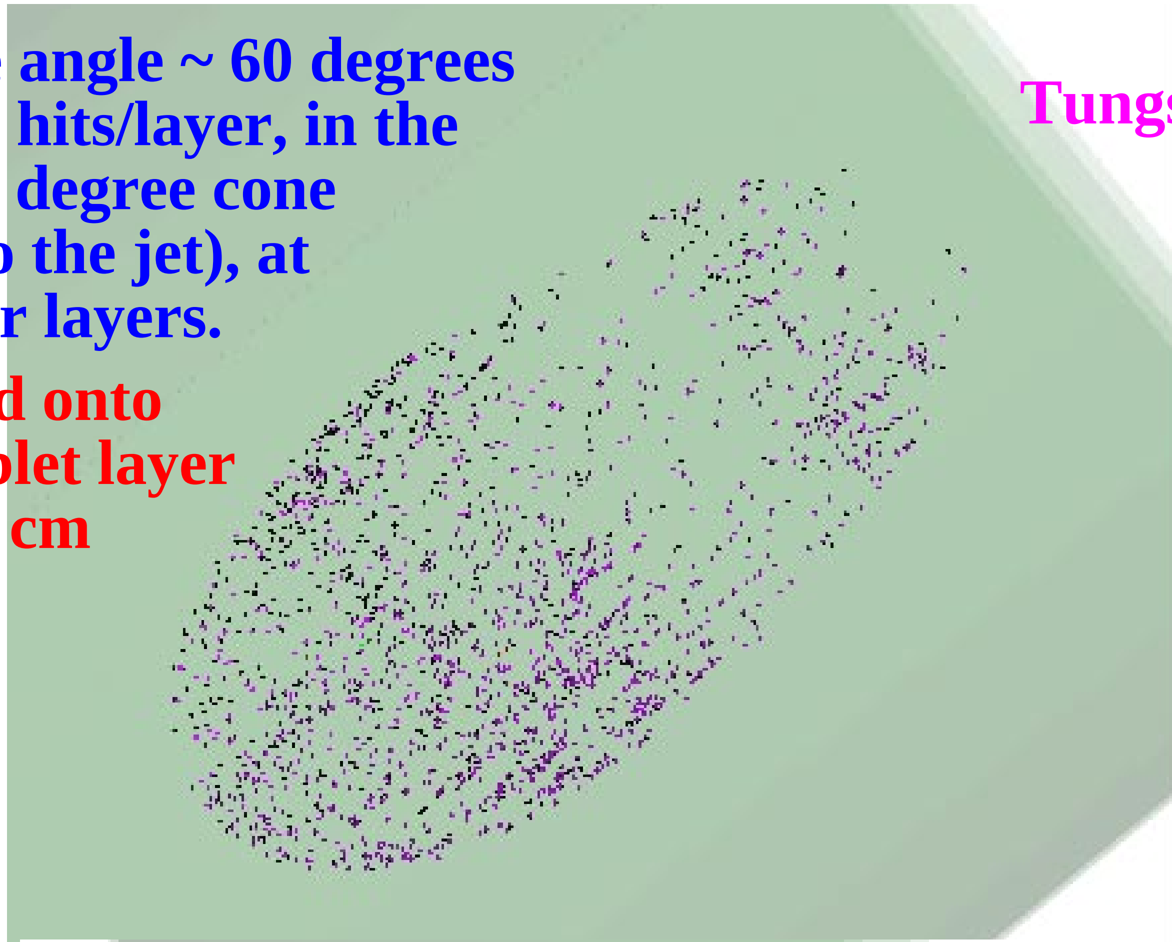
Pt cutoff and charge determination at the "hit" level.

Effect of requiring Pixel Microtelescope micro−coincidence

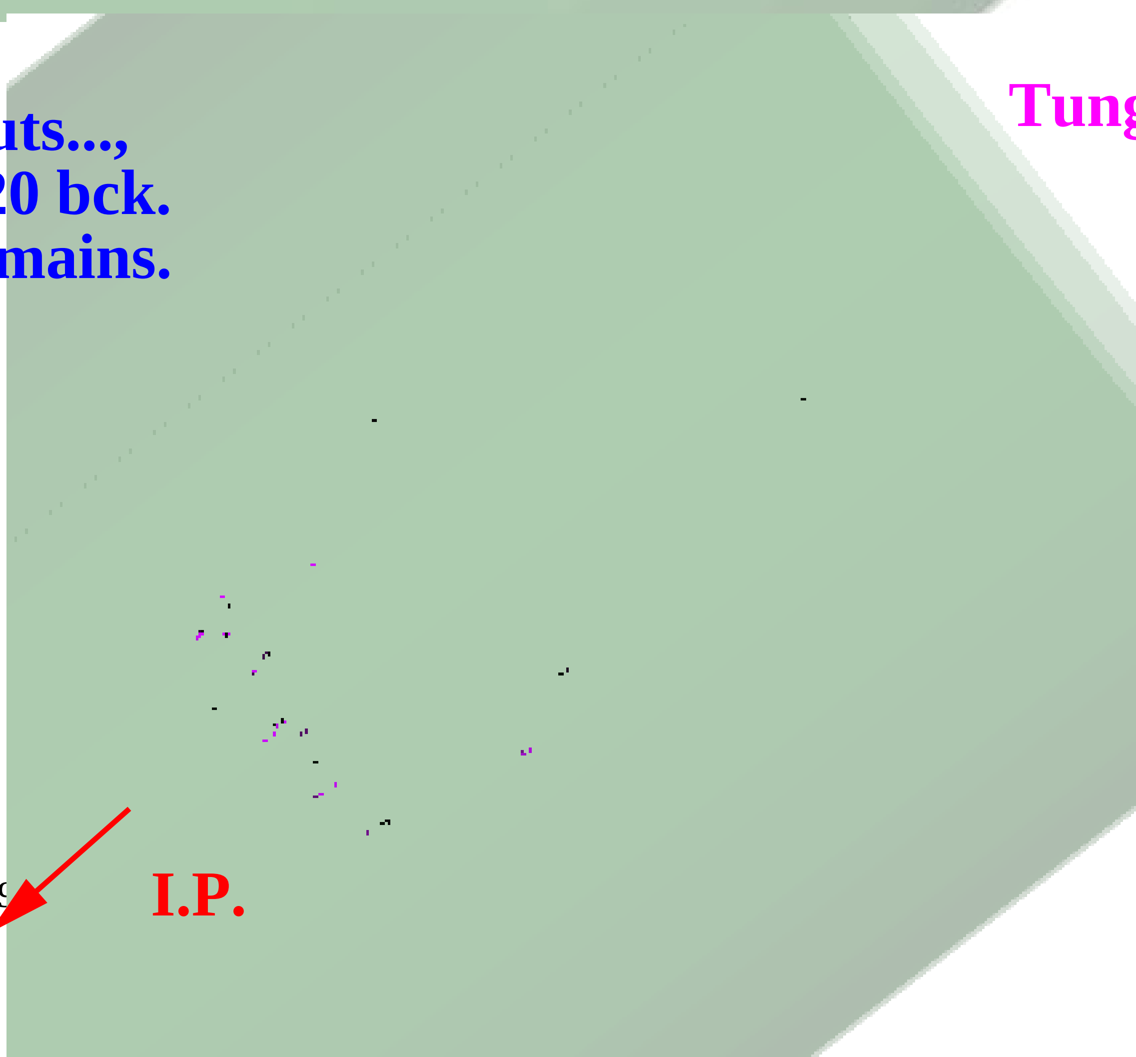
Paul Lebrun

At large angle ~ 60 degrees ~ 2,000 hits/layer, in the same 10 degree cone (perp. to the jet), at the outer layers.

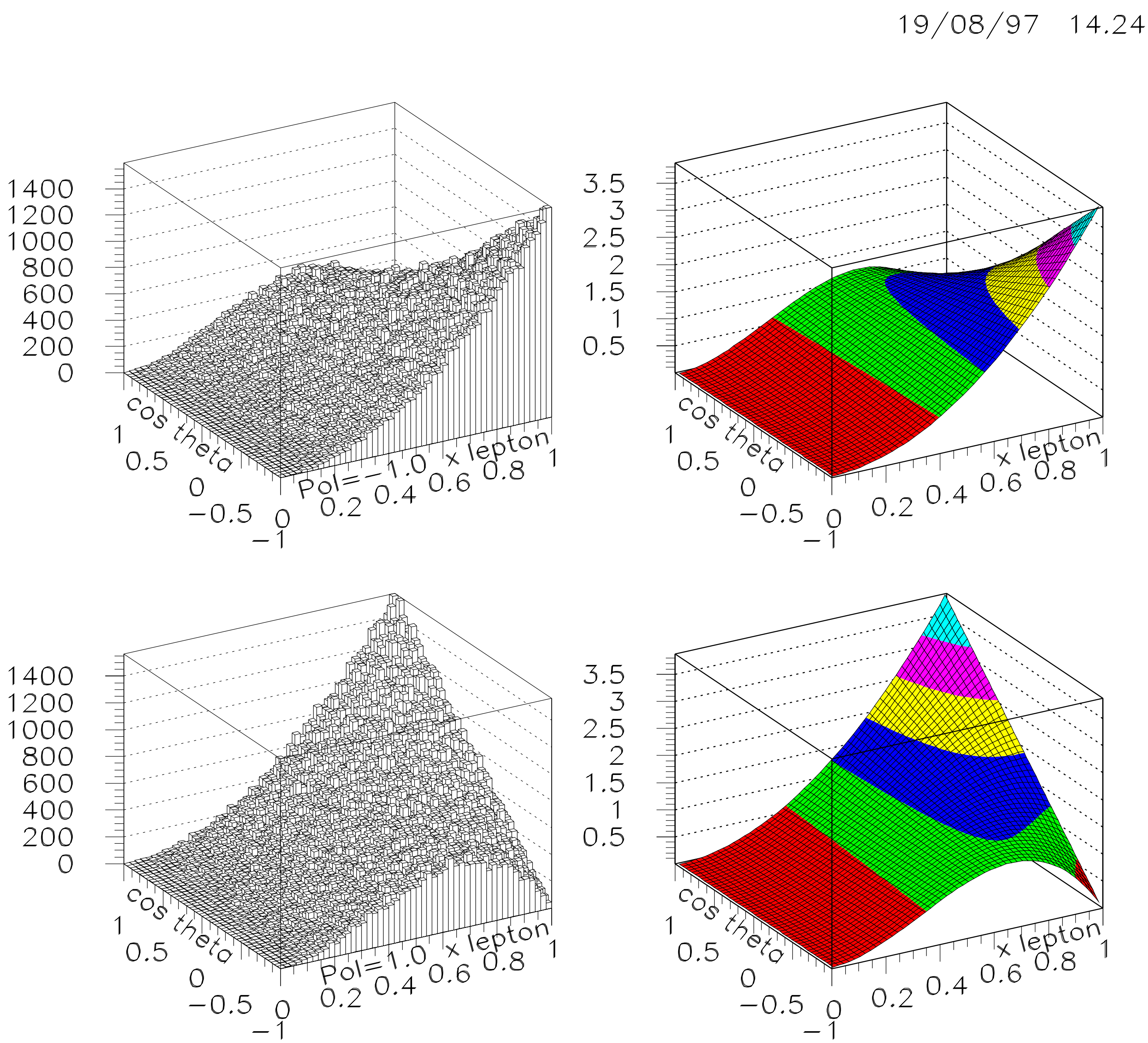
Projected onto one doublet layer at r = 25 cm



After cuts..., only ~20 bck. hits remains.



Electron energy and angle distributions in muon rest frame
Polarization = -1.0 and 1.0



Mu_geant - Program to simulate muon collider detectors

Rajendran Raja
Fermilab

International Workshop on Linear Colliders
Sitges, Barcelona
May,1999